

Search for heavy long-lived multicharged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector

M. Aaboud *et al.*^{*}
(ATLAS Collaboration)



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A search for heavy long-lived multicharged particles is performed using the ATLAS detector at the LHC. Data with an integrated luminosity of 36.1 fb^{-1} collected in 2015 and 2016 from proton-proton collisions at $\sqrt{s} = 13$ TeV are examined. Particles producing anomalously high ionization, consistent with long-lived massive particles with electric charges from $|q| = 2e$ to $|q| = 7e$, are searched for. No events are observed, and 95% confidence level cross-section upper limits are interpreted as lower mass limits for a Drell-Yan production model. Multicharged particles with masses between 50 and $980\text{--}1220$ GeV (depending on their electric charge) are excluded.

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I. INTRODUCTION

This article describes a search for heavy long-lived multicharged particles (MCPs) in $\sqrt{s} = 13$ TeV proton-proton collision data collected in 2015 and 2016 by the ATLAS detector at the CERN Large Hadron Collider (LHC) [1]. The search, conducted on a sample of data corresponding to an integrated luminosity of 36.1 fb^{-1} , is performed in the MCP mass range from 50 to 1400 GeV, for electric charges¹ $|q| = ze$, with charge numbers $2 \leq z \leq 7$. An observation of such particles, possessing an electric charge above the elementary charge e , would be a signature for physics beyond the Standard Model (SM). Several theoretical models predict such particles. AC-leptons, as predicted by the almost-commutative model [2], are pairs of SU(2) electroweak singlets with opposite electromagnetic charges and no other gauge charges of the SM, which makes them behave as heavy stable charged leptons. Technibaryons, predicted by the walking-technicolor model [3], are Goldstone bosons made of two techniquarks or two anti-techniquarks with an arbitrary value of the electric charge. The lightest technibaryon is expected to be stable in the absence of processes violating the technibaryon number conservation law. Doubly charged Higgs bosons are predicted by the left-right symmetric model [4] in Higgs triplets in a model postulating a right-handed version of the weak interaction. Its gauge

symmetry is spontaneously broken at a high mass scale, leading to parity-violation in the weak-interaction sector of the SM. Only leptonic decay modes would be characteristic of such particles, as shown in the model described in Ref. [5]. The $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ decays are assumed to be suppressed. The supersymmetric left-right model [5], which imposes lepton number conservation, predicts a light $H^{\pm\pm}$ boson with null lepton number, forbidding its decays to two same-sign leptons and making the $H^{\pm\pm}$ boson long-lived. Any observation of the particles predicted by the first two models could have implications for the formation of composite dark matter: the doubly charged particles (or, in general, particles with an even charge $|q| = 2ne$) could explain some excesses (e.g., positron excess) observed in direct and indirect searches for dark matter [6,7]. Particles with half-integer charge are considered in this search in order to allow continuous mass limits to be set between the $2e$ and $7e$ cases. So far, no such particles have been observed in cosmic-ray [8] or collider searches, including several recent searches at the Tevatron [9] and the LHC [10–12].

A purely electromagnetic coupling, proportional to the electric charge of the MCPs, is assumed for the production model. In this search the MCPs are assumed to live long enough to traverse the entire ATLAS detector without decaying, and thus the analysis exploits their muonlike signature, making the muon trigger a natural choice. They are highly ionizing, and thus generate an abnormally large ionization signal, dE/dx , which leads to their significant slowdown. Especially for MCPs with the highest charge and lowest mass values, this causes an event to not be triggered and/or MCPs to fail reconstruction as muons (this is the main reason for the search to be limited by the $z = 7$ MCPs from above). The addition of the missing-transverse-momentum trigger mitigates the first issue because a difference in energy deposited by the two MCPs in the

^{*}Full author list given at the end of the article.

¹Wherever a charge is quoted for exotic particles, the charge conjugate state is also implied.

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calorimeter will lead to a nonzero E_T vector sum and will make this trigger fire. Also, this trigger accepts events with high-mass MCPs that are too slow to fall within the muon-trigger timing window. The offline analysis searches for muonlike tracks with high dE/dx values in several sub-detector systems. The background expected from the SM processes (largely high- p_T muons) is estimated using a data-driven technique.

II. ATLAS DETECTOR

The ATLAS detector [13] covers nearly the entire solid angle around the collision point.² The inner tracking detector (ID) consists of a silicon pixel detector (pixel), a silicon microstrip detector (SCT) and a transition radiation tracker (TRT). The pixel detector was upgraded in 2014 with the insertion of an additional layer, the insertable B-layer (IBL) [14], mounted on a new beam pipe of smaller diameter. The pixel detector provides at least four precise space-point measurements per track. At normal incidence, the average charge released by a minimum-ionizing particle (MIP) in a pixel sensor is $\approx 20000 e^-$ ($\approx 16000 e^-$ for the IBL) and the charge threshold is set to $3500 e^-$ ($2500 e^-$ for the IBL) [15]. Signals are accepted if they are larger than this threshold. The time interval with the signal above the threshold is approximately proportional to the ionization charge and its dynamic range corresponds to 8.5 times (1.5 times for the IBL) the average charge released by a MIP if its track is normal to the silicon detectors and it deposits all its ionization charge in a single pixel. If this value is exceeded in the IBL, the electronics signals an excess with an overflow bit; if it is exceeded in the other three layers of the pixel detector, the hit information is not recorded due to electronics limitations (nor is the fact of the overflow). However, since the charge released by a particle crossing the pixel detector is rarely contained within just one pixel, the neighboring pixels preserve the spatial information of this hit. The SCT consists of four double-layer silicon sensors with binary readout architecture, each with a small stereo angle, typically providing eight measurements per track. The TRT, covering the pseudorapidity range $|\eta| < 2.0$, is a straw-tube tracking detector capable of particle identification via transition-radiation and ionization-energy-loss measurements [16]. A particle typically crosses 32 straws. Discriminators are used to compare the signal from a straw with a low threshold and a high threshold (HT). The HT is designed to discriminate

between energy depositions from transition-radiation photons and the energy loss of MIPs. Roughly three times the energy deposition of a MIP is needed to generate an HT hit. MCPs would produce a large number of HT hits along their trajectories due to their high ionizing power.

The ID is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, and by a high-granularity lead/liquid-argon (LAr) sampling electromagnetic calorimeter. An iron/scintillator tile calorimeter provides hadronic-energy measurements in the central pseudorapidity region. The end cap and forward regions are instrumented with LAr electromagnetic and hadronic calorimeters. The calorimeter system is surrounded by a muon spectrometer (MS) incorporating three superconducting toroidal magnet assemblies. The MS is instrumented with tracking detectors designed to measure the momenta of muons. Resistive-plate chambers (RPC) in the barrel region ($|\eta| < 1.05$) and thin-gap chambers (TGC) in the end cap regions ($1.05 < |\eta| < 2.4$) provide signals for the trigger. Monitored-drift-tube (MDT) chambers typically provide 20–25 hits per crossing track in the pseudorapidity range $|\eta| < 2.7$, from which a high-precision momentum measurement is derived. In each amplifier-shaper-discriminator channel, an analog-to-digital converter is used to measure the signal charge in the 18.5 ns integration gate following the initial threshold crossing [17]. Cathode-strip chambers complement the tracking capabilities of the MDTs in the high-rate forward regions.

A two-level trigger system is used to select interesting events [18]. The first trigger level is implemented in hardware and uses a subset of the detector information to reduce the event rate to a design value of at most 100 kHz. This is followed by the software-based high-level trigger, which reduces the event rate to about 1 kHz.

The amount of material in the ID varies from one-half to two radiation lengths. The overall amount of material traversed by an MCP up to the last measurement surface, which includes the calorimeters and the MS, may be as high as 75 radiation lengths. Muons typically lose 3 GeV penetrating the calorimeter system. The energy loss for MCPs with charge z would be z^2 times this value, i.e., up to 150 GeV for $z = 7$.

The muon transverse momentum measured by the MS after the energy loss in the calorimeters is denoted by p_T^μ , while transverse momentum of charged particles measured by the ID or the combination of the ID and MS is denoted by p_T . Charged-particle trajectories are reconstructed using standard algorithms. Since these algorithms assume particles with unit electric charge, the momenta of MCPs are underestimated by a factor z , as the track curvature is proportional to p_T/z .

III. SAMPLES OF SIMULATED EVENTS

Benchmark samples of simulated events with MCPs were generated for a mass of 50 GeV and for a range of

²ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

masses between 200 and 1400 GeV in steps of 200 GeV, for charges ze with $z = 2, 2.5, \dots, 7$. Leptonlike pairs of MCPs were generated via the lowest-order Drell-Yan (DY) process implemented in MADGRAPH5_aMC 2.3.3 [19] with only photon exchange included. This implementation of the DY production process models the kinematic distributions and determines the cross sections. Cross-section values for MCP pair production range from hundreds of picobarns (mass of 50 GeV, $z = 7$) down to a hundredth of a femtobarn (mass of 1400 GeV, $z = 2$). Events were generated using the NNPDF23LO [20] parton distribution functions with the A14 set of tuned parameters [21], and PYTHIA 8.205 [22,23] was used for hadronization and underlying-event generation.

Simulated samples with muons from $Z \rightarrow \mu\mu$ decays were generated using POWHEG-BOX v2 [24,25] interfaced to the PYTHIA 8.186 parton shower model. The AZNLO tuned parameters [26] were employed, with the CTEQ6L1 PDF set [27] for the modeling of nonperturbative effects. The EVTGEN 1.2.0 program [28] was utilized for the properties of b - and c -hadron decays.

A full GEANT 4 simulation [29,30] was used to model the response of the ATLAS detector. Each simulated hard-scattering event was overlaid with simulated minimum-bias events (“pileup”) generated with PYTHIA in order to reproduce the observed distribution of the number of proton-proton collisions per bunch crossing. The simulated events are reconstructed and analyzed in the same way as the experimental data.

IV. EVENT AND CANDIDATE SELECTIONS

The search relies on the ionization energy released by high-charge particles and measured in the pixel, TRT, and MDT subdetector systems. Acceptance is restricted to the pseudorapidity range $|\eta| < 2.0$ because of the TRT geometrical limitation.

The selection is logically divided into four steps: trigger and event selection, preselection, tight selection, and final selection. While the first two steps rely on muon and missing-transverse-momentum (E_T^{miss}) signals as well as event topology, the tight and final selection steps rely on the ionization estimators not available at the trigger level. These estimators are introduced later in this section. An event is considered to be a candidate event if it has at least one candidate MCP (a reconstructed particle, which satisfies all selection criteria).

A. Trigger and event selections

Events collected in 2015 and 2016 with a single-muon trigger with no isolation requirement and a transverse-momentum threshold of $p_T/z = 50$ GeV are considered. This trigger is only sensitive to particles with velocity $\beta = v/c > 0.6$ due to a timing window, within which particles must reach the MS, which limits the trigger efficiency.

To compensate for inefficiencies in the single-muon trigger, an additional calorimeter-based trigger that imposes a threshold on the magnitude of the E_T^{miss} was employed. The E_T^{miss} threshold was 70 GeV in 2015 and was raised twice in 2016, first to 90 GeV and later to 110 GeV. Particles reconstructed in the MS are not accounted for in the trigger E_T^{miss} calculation, which only takes into account energy deposited in the calorimeters. Large missing transverse momentum can be due to a major difference between the energy deposited by the two MCPs in the calorimeter leading to a nonzero E_T vector sum (because of significant random fluctuations of the deposited energy) and also due to an MCP-MCP system recoiling against a jet, given that the energy deposited by the MCPs in the calorimeter would not balance the jet energy.

If an event is selected by both of these triggers, it is assigned to the single-muon trigger for the following analysis. On average, the exclusive contribution of the E_T^{miss} trigger is about 20% of the overall number of triggered signal events.

B. Candidate track preselection

Each candidate track is required to be a “combined” muon, i.e., reconstructed by combining track segments in the ID with those in the MS. These candidate muons must satisfy the “medium” criteria defined in Ref. [31], have $p_T^\mu/z > 50$ GeV, and fall within the acceptance region of the TRT ($|\eta| < 2.0$).

In order to reduce the background of high-ionization signals from two or more tracks firing the same TRT straws or MDT tubes, each candidate is required not to have any adjacent tracks with $p_T/z > 0.5$ GeV within $\Delta R < 0.01$.

C. Ionization estimators and tight/final selections

The definitions of the tight and final selections require the introduction of ionization estimators.

The average specific energy loss, dE/dx , is described by the Bethe-Bloch formula [32]. Since a particle’s energy loss increases quadratically with its charge, an MCP would leave a very characteristic signature of high ionization in the detector. Estimates of dE/dx are evaluated for the pixel, TRT and MDT subdetector systems. The pixel dE/dx is calculated from the truncated mean of the dE/dx values of the clusters associated with the track, excluding the largest (one or two) dE/dx measurements. The TRT dE/dx is the truncated mean of the hit-level dE/dx estimates, derived from the time interval when the signal remains above the low threshold. Each drift tube of the MDT system provides a signal proportional to the charge from ionization; a truncated mean of these measurements is treated as the MDT dE/dx estimator. Apart from the mentioned tail truncations, calibrations and corrections of these dE/dx estimators include removal of their dependencies on geometrical quantities (pseudorapidity, distance between a particle track and an

anode wire for the TRT and MDT) and of those related to detector effects: dependence on the number of hits, radiation damage leading to run-by-run response difference for the pixel detector, detector occupancy for the pixel detector and TRT, difference between the response in the different detector sections for the MDT, etc.

The significance of the dE/dx variable in each sub-detector is defined by comparing the observed signal, dE/dx , with the average value for a highly relativistic muon:

$$S(dE/dx) = \frac{dE/dx - \langle dE/dx \rangle_\mu}{\sigma(dE/dx)_\mu}.$$

Here $\langle dE/dx \rangle_\mu$ and $\sigma(dE/dx)_\mu$ represent, respectively, the mean and the root-mean-square width of the dE/dx

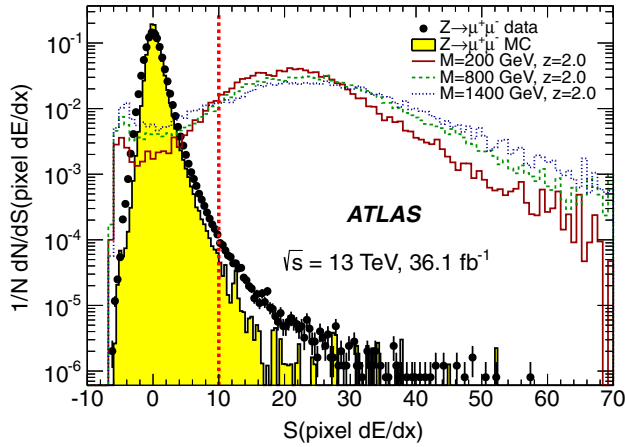
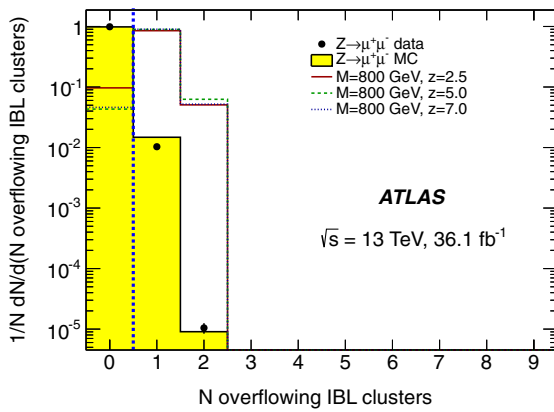


FIG. 1. Normalized distributions of the dE/dx significance in the pixel system, $S(\text{pixel } dE/dx)$ for muons from $Z \rightarrow \mu\mu$ events (data and simulation) and for simulated MCPs passing the preselection requirements. Signal distributions are shown for $z = 2$ and masses of 200, 800, and 1400 GeV. The red dotted line indicates the threshold of the selection criterion for the $z = 2$ search case.



distribution for such muons in data. To calculate these two parameters, a control sample of muons was obtained from $Z \rightarrow \mu\mu$ events. The muon selection is the same as in the analysis selection discussed in Sec. IV B. Also, muons are required to belong to an oppositely charged pair with dimuon mass between 81 and 101 GeV. These requirements effectively suppress muons from other processes.

In addition to the dE/dx estimates, the number of IBL clusters with at least one hit in overflow (called in the rest of the paper, for simplicity, the number of overflowing IBL clusters) and the fraction of HT TRT hits (f^{HT}) are estimators of the energy loss and are used in the tight selection.

As seen in Fig. 1, $S(\text{pixel } dE/dx)$ is a powerful discriminator for particles with $z = 2$. The signal region of the tight selection is defined by requiring $S(\text{pixel } dE/dx)$ greater than 10. For higher values of z , the pixel readout saturates and the corresponding hits are not recorded. Therefore, to search for particles with $z > 2$, the number of overflowing IBL clusters and f^{HT} (see Fig. 2) are used as discriminating variables instead, with the signal regions of the tight selection defined by requiring at least one overflowing IBL cluster and f^{HT} to be above 0.5.

For both the $z = 2$ and $z > 2$ search cases, the tight selection criteria reduce the background contribution (mainly from the high- p_T muons) by at least 3 orders of magnitude, while keeping the signal efficiency above 90% relative to the efficiency obtained in the previous selection step.

In the final selection, $S(\text{MDT } dE/dx)$ and $S(\text{TRT } dE/dx)$ are used as additional discriminating variables to separate signal from background. Figure 3 shows the distributions of these variables for muons from $Z \rightarrow \mu\mu$ events compared with those expected from signal particles with different charges ($z = 2.0, 4.5$, and 7.0) and a mass of 800 GeV. It demonstrates that there is good separation between signal and background, which increases with increasing charge. The $S(\text{MDT } dE/dx)$ distribution shape broadens noticeably

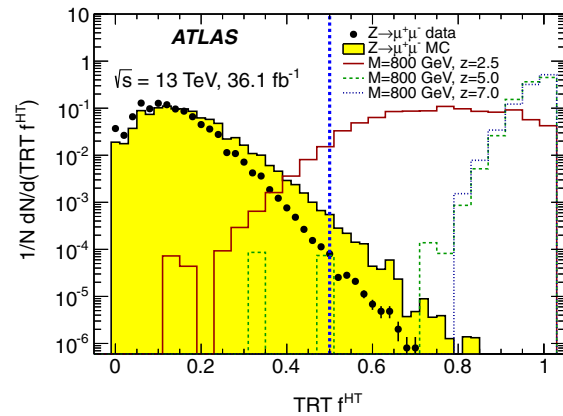


FIG. 2. Normalized distributions of the number of overflowing IBL clusters (left) and f^{HT} (right) for muons from $Z \rightarrow \mu\mu$ events (data and simulation) and for simulated MCPs passing the preselection requirements. Signal distributions are shown for $z = 2.5, 5.0, 7.0$ and a mass of 800 GeV. The blue dotted lines indicate the thresholds of the selection criteria for the $z > 2$ search case.

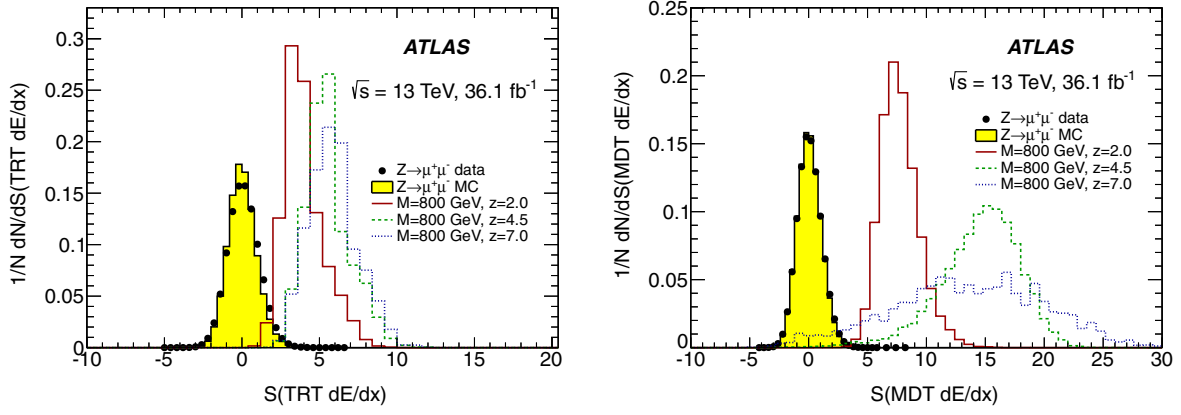


FIG. 3. Normalized distributions of the dE/dx significance in the TRT, $S(\text{TRT } dE/dx)$, (left) and in the MDT, $S(\text{MDT } dE/dx)$, (right) for muons from $Z \rightarrow \mu\mu$ events (data and simulation) and for simulated MCPs passing preselection requirements. Signal distributions are shown for $z = 2.0, 4.5$, and 7.0 , for a mass of 800 GeV .

with charge because, relative to typical muons, MCPs produce a larger number of δ -rays, which give early-time hits in adjacent drift tubes. This results in the δ -rays' ionization loss being measured instead of the MCP's loss, reducing the total ionization measured along the track. The detailed detector response to these high-charge particles may not be well simulated due to imperfect modeling of the saturation effects. However, since these two detectors (TRT and MDT) do not lose signal at saturation, their most probable dE/dx values are higher than those of $z = 2$ particles.

During the 2012 data-taking period, gas leaks started to develop in TRT pipes, located mostly in inaccessible areas, making their repair impossible [33]. Due to the high cost of the xenon-based gas mixture, leaking modules were supplied with an argon-based mixture instead. The simulation does not fully model this change, resulting in a slightly narrower TRT dE/dx distribution in simulation than in data. This is a small effect because the ratio of signal amplitude to the low threshold for the argon-filled straws was tuned to be the same

as for xenon-filled ones. It is accounted for in the systematic uncertainties calculation in Sec. VII B.

The energy loss in the calorimeters is not used in the search because they have coarser granularity than the tracking detectors and, thus, worse energy-loss resolution.

Ionization-estimators discrepancies between data and simulation are accounted for as systematic uncertainties as described in Sec. VII B.

Two-dimensional distributions of $S(\text{MDT } dE/dx)$ versus $S(\text{TRT } dE/dx)$ are shown for data and simulated signal events in Fig. 4 for candidates passing the tight selection for $z = 2$ (left) and $z > 2$ (right). As seen, the subdetector signatures are different for the two samples, and thus the final signal regions are chosen differently. They are defined by $S(\text{TRT } dE/dx) > 2.5$ and $S(\text{MDT } dE/dx) > 4$ for candidates selected as $z = 2$ and by $S(\text{TRT } dE/dx) > 3.5$ and $S(\text{MDT } dE/dx) > 4$ for candidates selected as $z > 2$. The selection was optimized using only simulated samples and $Z \rightarrow \mu\mu$ data control samples without examining the signal region in the data.

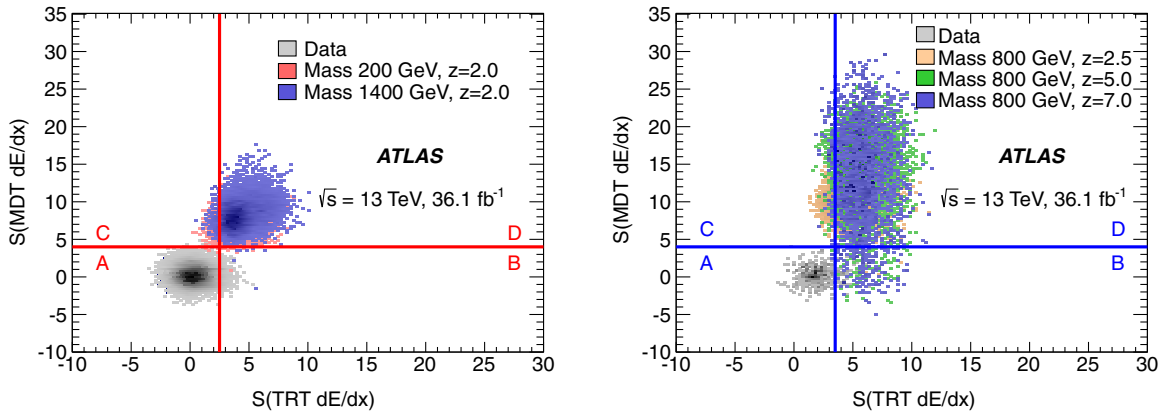


FIG. 4. $S(\text{MDT } dE/dx)$ versus $S(\text{TRT } dE/dx)$ after the $z = 2$ (left) and $z > 2$ (right) tight selections. The distributions of the data and the simulated signal samples (for charges $z = 2.0, 2.5, 5.0$, and 7.0 , and masses of $200, 800$, and 1400 GeV) are shown. The meaning of the A, B, C and D regions is discussed in the text.

TABLE I. Summary of preselection, tight selection and final selection requirements.

	Candidate track preselection		Tight selection	Final selection
Requirements	$z = 2$	Combined muon with “medium” identification criteria, $p_T^\mu/z > 50$ GeV,	Preselected candidate with $S(\text{pixel } dE/dx) > 10$	Tightly selected candidate with $S(\text{TRT } dE/dx) > 2.5$, $S(\text{MDT } dE/dx) > 4$
	$z > 2$	$ \eta < 2.0$, no other tracks with $p_T/z > 0.5$ GeV within $\Delta R < 0.01$	Preselected candidate with ≥ 1 overflowing IBL cluster, $f^{\text{HT}} > 0.5$	Tightly selected candidate with $S(\text{TRT } dE/dx) > 3.5$, $S(\text{MDT } dE/dx) > 4$

A summary of the preselection, tight selection and final selection requirements for candidate tracks is presented in Table I.

V. EXPECTED BACKGROUND ESTIMATION

The source of potential background is of an instrumental origin: it consists mainly of muons with ionization randomly fluctuating toward larger values due to detector occupancy effects (a large number of particles losing their energy in the same detector elements) and δ -ray yields. The expected background rate is estimated with two methods.

For the $z = 2$ search case, it is estimated using an ABCD method [34]. According to this method, the plane of $S(\text{TRT } dE/dx)$ and $S(\text{MDT } dE/dx)$ is divided into regions A, B, C, and D using the final selection cuts as shown in Fig. 4. Region D is defined as the signal region, with regions A, B, and C as control regions.

If two or more particles contribute to the same event on the ABCD plane, only one is retained and shown on the plane according to a “D-C-B-A- p_T^μ ” ranking to avoid double-counting events. It consists in choosing the first particle found when considering region D then C, B, and finally A (ranked from the most populated quadrant to the least populated one in signal simulation). If there are two or more particles in the event and in the same region, the highest- p_T^μ one is chosen.

For the $z = 2$ search, the expected number of background events in the D region, $N_{\text{data}}^{\text{D expected}}$, is estimated from the numbers of observed data events in regions A, B, and C ($N_{\text{data}}^{\text{A,B,C observed}}$):

$$N_{\text{data}}^{\text{D expected}} = \frac{N_{\text{data}}^{\text{B observed}} \times N_{\text{data}}^{\text{C observed}}}{N_{\text{data}}^{\text{A observed}}}.$$

The same method is not used for the $z > 2$ search case, because $N_{\text{data}}^{\text{C observed}} = 0$ [see Fig. 4 (right)], which would lead to a large statistical uncertainty in $N_{\text{data}}^{\text{D expected}}$. Instead, a method which employs sidebands of the two discriminating variables is used [10]. Here, $N_{\text{data}}^{\text{D expected}}$ is estimated from the number of observed events in region B and the probability f to find a particle with $S(\text{MDT } dE/dx) > 4$ in a single event:

$$N_{\text{data}}^{\text{D expected}} = N_{\text{data}}^{\text{B observed}} \times f.$$

The probability f is derived from the cumulative $S(\text{MDT } dE/dx)$ distribution for preselected muons in data with an anti-tight selection applied as shown in Fig. 5. The anti-tight selection is defined by inverting one of the tight selection criteria: a muon must have $f^{\text{HT}} < 0.5$ or must not have any overflowing IBL clusters. If two or more muons are present in the same event, only the highest- p_T^μ muon is chosen to contribute to the distribution.

This method relies on the fact that $S(\text{MDT } dE/dx)$ is not correlated with the tight selection quantities in background events. A check was performed to demonstrate the absence of such correlations: the distributions of $S(\text{pixel } dE/dx)$, number of IBL clusters in overflow, f^{HT} and $S(\text{TRT } dE/dx)$ for muons in data with low $S(\text{MDT } dE/dx)$ values (between -10 and 0) were compared with those for muons with high $S(\text{MDT } dE/dx)$ values (between 0 and 10). An agreement at a level of 98.5% between the two cases is found, which shows that there are no correlations between ionization estimators in different subdetectors for background. Also, an additional check was performed to make sure that the shapes of cumulative $S(\text{MDT } dE/dx)$ distributions for the cases of

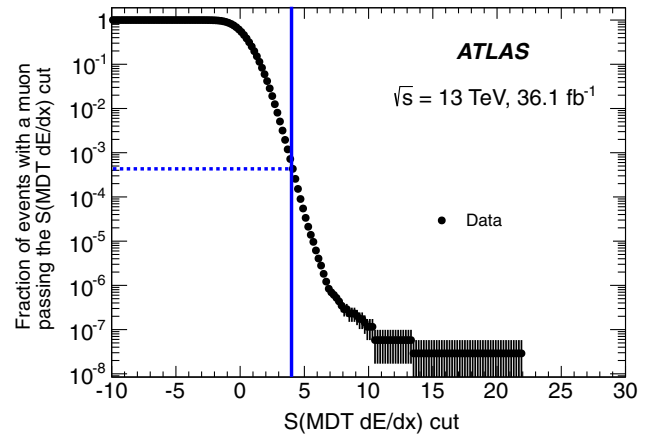


FIG. 5. Cumulative $S(\text{MDT } dE/dx)$ distribution with the anti-tight selection applied, used to calculate the probability f to find a particle with $S(\text{MDT } dE/dx) > 4$. The resulting value of f is indicated by the blue dashed line.

TABLE II. Expected background contribution (in events) to the D region in data for the $z = 2$ selection, as well as quantities used for its calculation. The observed contribution is shown in the rightmost column.

$N_{\text{data}}^{\text{A observed}}$	$N_{\text{data}}^{\text{B observed}}$	$N_{\text{data}}^{\text{C observed}}$	$N_{\text{data}}^{\text{D expected}}$	$N_{\text{data}}^{\text{D observed}}$
22117	379	9	$0.15 \pm 0.05 \text{ (stat.)} \pm 0.10 \text{ (syst.)}$	0

TABLE III. Expected background contribution (in events) to the D region in data for the $z > 2$ selection, as well as quantities used for its calculation. The observed contribution is shown in the rightmost column.

$N_{\text{data}}^{\text{B observed}}$	f	$N_{\text{data}}^{\text{D expected}}$	$N_{\text{data}}^{\text{D observed}}$
66	4.3×10^{-4}	$(2.9 \pm 0.4 \text{ (stat.)} \pm 2.2 \text{ (syst.)}) \times 10^{-2}$	0

anti-tight (see Fig. 5) and regular tight selections lay within their statistical uncertainties. Any residual differences are attributed to a systematic uncertainty as explained in Sec. VII A.

The expected background contributions to the D regions and quantities used for their calculation are shown in Tables II and III for the $z = 2$ and $z > 2$ search cases, respectively. Systematic uncertainties in these values are estimated according to the method discussed in Sec. VII A.

In principle, the absence of candidates in the C region may be translated into a Poisson upper limit at 95% confidence level of 2.996 events, and the expected background yield can be further estimated with the $z = 2$ method. However, this results in a less precise estimate with the upper limit of 0.5 background events, which makes the usage of the $z > 2$ method more favorable.

VI. SIGNAL EFFICIENCY

The cross-section limit is inversely proportional to the integrated luminosity of the analyzed data times the overall signal efficiency, which includes trigger and selection efficiencies. This efficiency, as estimated from simulation, is shown in Fig. 6 for the signal samples used in this analysis.

The fraction of signal events satisfying the cumulative selection requirements is given in Table IV for several examples.

Several factors contribute to the efficiency dependencies on mass and charge of the MCPs. For low masses, the $|\eta| < 2.0$ selection requirement and especially the p_T^μ/z requirement are the main sources of efficiency loss. This p_T^μ/z implied selection can be as high as approximately $p_T^\mu > 50 \times 7 = 350$ GeV, where 7 is the highest charge value used in the analysis. For high masses, the requirement to reach the MS with a velocity β which satisfies the trigger timing window is the primary reason for the reduction in efficiency. Also, high ionization loss makes particles slow down: they may not fall within the trigger timing window or may lose all their kinetic energy before reaching the MS. The charge dependence of the efficiency results from higher ionization and the higher effective p_T^μ/z selection, which are augmented by the factors z^2 and z , respectively. Also, the increased production of δ -rays at higher charges leads to a smaller number of reconstructed combined muons. For events with only one MCP reaching the MS, the E_T^{miss} will be larger for heavier and/or higher-charged MCPs and therefore the E_T^{miss} trigger will be more likely to fire in such events.

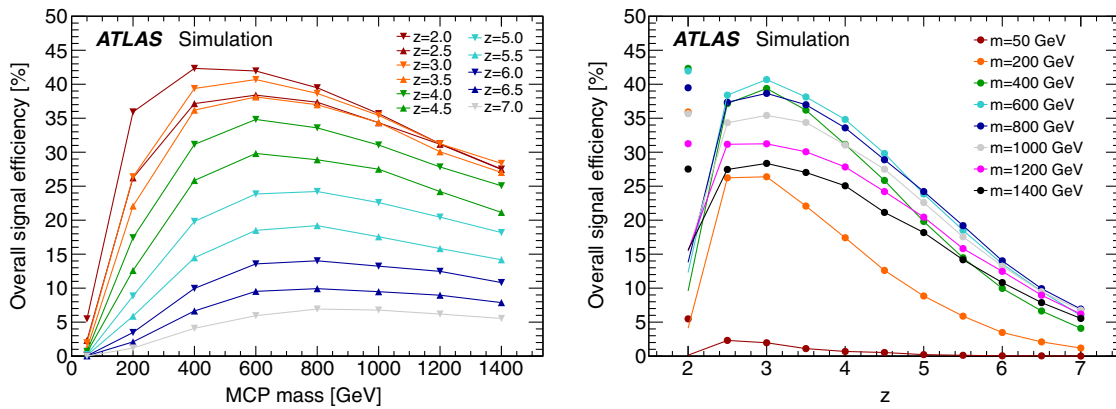


FIG. 6. The signal efficiencies for different MCP charges and masses for the DY production model versus, respectively, mass (left) and charge (right) values. Despite the analysis being performed separately for $z = 2$ and $z > 2$ MCPs, it is still sensitive to MCPs with $2 < z < 2.5$. In the right figure, the efficiencies at $z = 2.0$ indicated by the continuous lines correspond to the efficiency values as if the $z > 2$ selection was applied to the $z = 2$ samples, thus denoting the conservative efficiency estimates for the $2.0 < z < 2.5$ particles.

TABLE IV. Fractions of signal events with at least one MCP candidate, which satisfy the given requirements (including all previous selection requirements). The uncertainties quoted are statistical only.

Signal benchmark point		Trigger selection [%]	Candidate event selection [%]	Tight selection [%]	Final selection [%]
z	Mass [GeV]				
2.0	200	51.6 ± 0.3	41.6 ± 0.3	39.2 ± 0.3	35.9 ± 0.3
	800	54.5 ± 0.3	44.6 ± 0.3	41.3 ± 0.3	39.5 ± 0.3
	1400	39.9 ± 0.3	32.0 ± 0.3	28.4 ± 0.3	27.5 ± 0.3
4.5	200	19.2 ± 0.2	13.8 ± 0.2	13.4 ± 0.2	12.6 ± 0.2
	800	44.3 ± 0.3	31.3 ± 0.3	30.2 ± 0.3	28.9 ± 0.3
	1400	33.6 ± 0.3	22.6 ± 0.2	22.1 ± 0.2	21.1 ± 0.2
7.0	200	5.5 ± 0.1	1.42 ± 0.07	1.4 ± 0.1	1.19 ± 0.07
	800	21.0 ± 0.2	8.3 ± 0.2	7.9 ± 0.2	6.9 ± 0.2
	1400	18.3 ± 0.2	6.7 ± 0.1	6.5 ± 0.1	5.5 ± 0.1

VII. UNCERTAINTIES IN THE BACKGROUND ESTIMATION AND SIGNAL YIELD

Uncertainties in the background estimate, the signal selection efficiency, and the integrated luminosity affect the sensitivity of the search for MCPs. The contributions of these systematic uncertainties are described below.

A. Background estimation uncertainty

To assess a systematic uncertainty in the expected number of background events, so-called “dead regions” are introduced in the ABCD plane (see Fig. 7, left), and then the background estimate is recalculated for several dead-region choices using the two methods described in Sec. V. The dead regions used are: $S_{\text{lower}}^{\text{MDT}} < S(\text{MDT } dE/dx) < 4.0$ with $S_{\text{lower}}^{\text{MDT}} = 2.0, 2.5, 3.0,$ and 3.5 for both the $z = 2$ and $z > 2$ cases; and $S_{\text{lower}}^{\text{TRT}} < S(\text{TRT } dE/dx) < S_{\text{upper}}^{\text{TRT}}$ with $S_{\text{lower}}^{\text{TRT}} = 0.5, 1.0, 1.5,$ and 2.0 for the $z = 2$ case and $S_{\text{upper}}^{\text{TRT}} = 1.5, 2.0, 2.5,$ and 3.0 for the $z > 2$ case. The entries

inside the dead regions do not contribute to the background estimate used to assess the systematic uncertainty. This method provides an insight into any possible correlations between the two variables used to construct the ABCD plane.

The maximum differences (calculated over several dead regions) between a new background expectation in the D region and the nominal one are 67% (0.1 events) and 3.4% (10^{-3} events) for the $z = 2$ and $z > 2$ cases, respectively, and are treated as systematic uncertainties in the estimation of the expected background.

An additional uncertainty is assigned for the $z > 2$ case due to a mismatch between the spectra of the fraction of events with a muon passing the $S(\text{MDT } dE/dx)$ cut for the tight and anti-tight selections (see Fig. 7, right) at $S(\text{MDT } dE/dx)$ values close to 4. Both distributions were fit with a $p_0 \times e^{p_1 x + p_2}$ function (a first-degree polynomial in the exponent was chosen for simplicity) within the range of $3 < S(\text{MDT } dE/dx) \text{ cut} < 5$, where x represents the $S(\text{MDT } dE/dx)$ cut value and $p_0, p_1,$ and p_2 are free fit

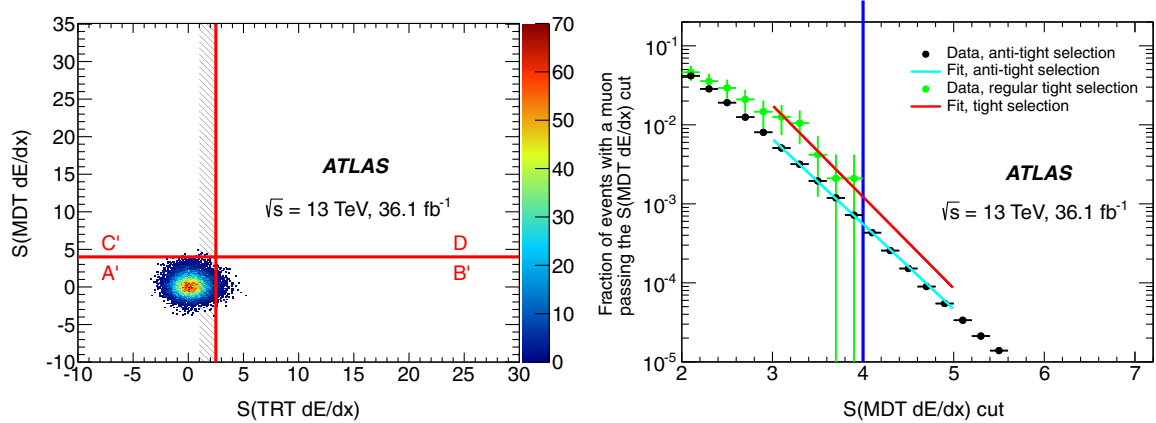


FIG. 7. Left: ABCD plane (for the $z = 2$ case) used to assess the systematic uncertainty in the expected number of background events. Entries inside the “dead region” (here within $1.0 < S(\text{TRT } dE/dx) < 2.5$, shown by black shading) do not contribute to the background estimate used to assess the systematic uncertainty. Right: overall $S(\text{MDT } dE/dx)$ distribution with the anti-tight selection applied (black points) and with the regular tight selection applied (green points). Both distributions are shown zoomed in around the final selection cut (shown by a solid blue vertical line) and are fit with $p_0 \times e^{p_1 x + p_2}$ functions to quantify their difference at $S(\text{MDT } dE/dx) = 4$.

parameters. The difference between the two fits at $S(\text{MDT } dE/dx) = 4$ is used to assign an additional 75% systematic uncertainty (0.022 events).

Summarizing the above, the final systematic uncertainties in the estimation of the expected background are 67% for $z = 2$ and 75% for $z > 2$.

B. Signal yield uncertainty

Several sources of systematic uncertainty in the signal efficiency are considered. The most significant uncertainties are those due to imperfect agreement between data and simulation, the trigger efficiency, and the parametrization of the parton distribution function used in the signal generation.

The uncertainty due to the disagreement between data and simulation is evaluated by varying the signal acceptance requirements used in the analysis. Several considerations motivate these variations. The uncertainty in the amount of material in front of the MS, which is about 1% [35], propagates into an uncertainty in the selection efficiency due to the slowing down of particles, and is covered by varying the p_T^μ requirement. When considering the $Z \rightarrow \mu\mu$ dE/dx distributions together with those of the signal, the lower parts of the dE/dx ranges are the most important for determining the signal efficiency. These correspond to the cores of the $Z \rightarrow \mu\mu$ distributions and are the most relevant because if there is good agreement between data and simulation in that dE/dx range (below the corresponding selection cut), the signal efficiencies will agree between the data and simulation. The variation applied to the nominal p_T^μ requirement is p_T^μ value by $\pm 3\%$.

In addition, the mean and the root-mean-square width of the distributions in $Z \rightarrow \mu\mu$ events disagree between data and simulation, and the ionization estimators may be mismodeled. These are accounted for by the following variations of the signal selection criteria:

- (i) number of overflowing IBL clusters by $\pm 0.5\%$,
- (ii) $S(\text{pixel } dE/dx)$ by $\pm 25\%$,

(iii) f^{HT} by $\pm 40\%$,

(iv) $S(\text{TRT } dE/dx)$ by $\pm 15\%$,

(v) and $S(\text{MDT } dE/dx)$ by $\pm 3\%$.

The values of these variations are obtained by averaging the bin-by-bin ratios of $Z \rightarrow \mu\mu$ yields in data to those in simulation (see Figs. 1–3) in the cores of the corresponding distributions (within $\pm 3\sigma$ with respect to the position of the mean of each distribution). The total systematic uncertainties in the efficiency arising from these variations range between 5% and 80%, where the largest uncertainty corresponds to lower-mass $z = 2.5$ signal samples, which are fairly sensitive to the f^{HT} variation.

The uncertainty in the trigger efficiency also has several sources, including an uncertainty in the muon-trigger efficiency ($< 0.5\%$), accounting for differences between triggering on the same muons in data and simulation, and an uncertainty in the E_T^{miss} trigger efficiency (23% on average). This second uncertainty depends on the accuracy of modeling the E_T^{miss} turn-on curve, and is sensitive to the offline E_T^{miss} reconstruction. The former (9.4%) was assessed by comparing the turn-on curves of the corresponding triggers in data and simulation using $Z \rightarrow \mu\mu$ samples and taking the largest difference between all pairs. The latter (21% on average) was assessed using the offline E_T^{miss} spectra (in events triggered exclusively by the E_T^{miss} trigger), varied to account for any possible uncertainties in the E_T^{miss} term. There is also a β -dependent uncertainty originating from uncertainties in the modeling of the muon-trigger timing for particles with $\beta \ll 1$. In order to improve the description of the trigger simulation, parametrized corrections were applied to the probability for MCPs to fire the RPC trigger. To assess the uncertainty, the parameters of these corrections were varied. The β value of particles was varied between the true generated value and the one reconstructed in the MS from the hypothesized mass and measured momentum. The time interval needed for a signal particle to reach the RPC trigger planes was varied by the root-mean-square width of the timing

TABLE V. Overview of the most significant individual contributions (in %) to the overall systematic uncertainties in the signal selection efficiency, as well as the resulting values of the relative uncertainties (rightmost column).

Signal benchmark point		Data-simulation comparison [%]	Trigger efficiency [%]	PDF parametrization [%]	Selection efficiency overall uncertainty [%]
z	Mass [GeV]				
2.0	200	12	0.9	6.5	14
	800	7.2	3.6	10	13
	1400	6.1	5.0	17	19
4.5	200	8.9	1.4	6.9	12
	800	5.7	2.4	11	12
	1400	5.9	10.2	17	21
7.0	200	9.3	3.1	7.2	14
	800	6.6	8.2	11	16
	1400	6.7	5.6	18	21

distribution for muons measured in the full $Z \rightarrow \mu\mu$ data sample. The uncertainty, assessed as the maximum relative difference between the nominal efficiency values and those obtained after the variations, ranges up to 1% for signal particles with the highest charges and masses. For the TGC trigger, no mismatch between the timing distributions in data and simulation was observed; therefore the trigger efficiency as obtained from simulation can be trusted.

For MCPs with β significantly less than 1 the drift time in the TRT and MDT could be mismeasured (due to the arrival time of the particle to the detector), worsening the momentum resolution, but TRT and MDT simulations model this effect. In the TRT, the effect is hardly noticeable due to the relatively small distance between the interaction point and the TRT. An MCP traveling one meter gets delayed by 0.6 ns for $\beta = 0.8$, while the TRT time bin is 3.1 ns. Also, the track reconstruction accepts hits within a timing uncertainty of $\pm(3-4)$ ns. The time difference is larger for the MS (up to 7 ns); however, the total drift time in MDT, with drift tubes of radius 15 mm, is about 700 ns, and thus any likely difference between data and simulation would not contribute significantly to the track reconstruction efficiency.

The NNPDF23LO parton distribution function (PDF) was varied within its error sets, each with a slightly different parametrization. These variations were translated into an uncertainty in the signal efficiency, ranging from 6% for low-mass MCPs to 18% for MCPs with the highest mass.

A 2.1% uncertainty was assigned to the integrated luminosity used for this analysis. This uncertainty is derived, following a methodology similar to that detailed in Ref. [36], from a calibration of the luminosity scale using x - y beam-separation scans.

A subset of contributions from the separate sources of the most significant systematic uncertainties in the signal selection efficiency, as well as the resulting values of

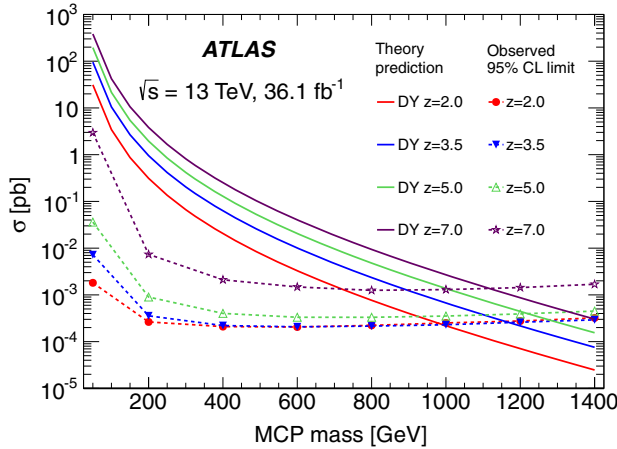


FIG. 8. Observed 95% C.L. cross-section upper limits and theoretical cross sections as functions of the leptonlike MCP's mass for several values of z between 2 and 7.

TABLE VI. Observed 95% C.L. lower mass limits of leptonlike MCPs for the Drell-Yan production model.

	z										
	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Lower mass limit [TeV]	0.98	1.06	1.13	1.17	1.20	1.22	1.22	1.21	1.19	1.16	1.12

overall systematic uncertainties, are shown in Table V for several benchmark points.

VIII. RESULTS

No candidate events with MCPs were found for either the $z = 2$ search or the $z > 2$ search. The results are consistent with the expectation of 0.15 ± 0.05 (stat.) ± 0.10 (syst.) and $(2.9 \pm 0.4$ (stat.) ± 2.2 (syst.)) $\times 10^{-2}$ background events, respectively. Since the number of events expected from background is very small and no signal events were found, the observed and expected limits are practically identical.

The limits are computed with the ROOSTATS framework [37], which uses the CL_s method [38] to discriminate between the background-only hypothesis and the signal-plus-background hypothesis, and determines exclusion limits for various MCP scenarios. The signal selection efficiency, luminosity, expected and observed numbers of events and their uncertainties (as well as signal leakages (fractions of the signal distributions outside the D region of the ABCD plane), handled as nuisance parameters, are

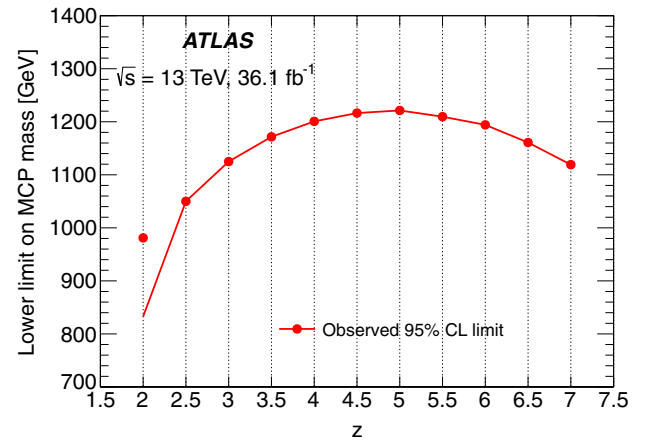


FIG. 9. Observed 95% C.L. lower mass limits of leptonlike MCPs for charges $z \in [2, 7]$ with a Drell-Yan pair-production model. The mismatch between the left end of the continuous line and the marker at $z = 2.0$ (a shift by 150 GeV) is due to the difference in efficiencies between the cases where the $z = 2$ and $z > 2$ selections are applied to the $z = 2.0$ samples, making this line segment constitute a conservative mass limit for $2.0 < z < 2.5$ particles.

taken as input for pseudoexperiments, resulting in an observed limit at 95% confidence level (C.L.).

The measurement excludes the DY model of leptonlike MCP pair production over wide ranges of tested masses. Figure 8 summarizes the observed 95% C.L. cross-section limits as a function of mass for several MCP charges and compares them with those predicted by the DY model.

For this model, the cross-section limits can be transformed into mass exclusion regions from 50 GeV up to the values in Table VI. Figure 9 demonstrates the dependence of the lower mass exclusion limits on MCP charge values. The mass limits are obtained from the intersection of the observed limits and the theoretical cross-section values.

IX. CONCLUSION

This article reports on a search for long-lived multi-charged particles produced in proton-proton collisions with the ATLAS detector at the LHC. The search uses a data sample with a center-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 36.1 fb^{-1} . Leptonlike particles are searched for with electric charges from $|q| = 2e$ to $|q| = 7e$ penetrating the full ATLAS detector and producing anomalously high ionization signals in multiple detector elements. Less than one background event is expected and no events are observed. Upper limits are derived on the cross sections using a Drell-Yan production model and exclude leptonlike multicharged particles with masses between 50 and 980–1220 GeV.

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M. Aaboud,^{34d} G. Aad,⁹⁹ B. Abbott,¹²⁵ D. C. Abbott,¹⁰⁰ O. Abdinov,^{13,a} B. Abeloos,¹²⁹ D. K. Abhayasinghe,⁹¹ S. H. Abidi,¹⁶⁴ O. S. AbouZeid,³⁹ N. L. Abraham,¹⁵³ H. Abramowicz,¹⁵⁸ H. Abreu,¹⁵⁷ Y. Abulaiti,⁶ B. S. Acharya,^{64a,64b,b} S. Adachi,¹⁶⁰ L. Adam,⁹⁷ L. Adamczyk,^{81a} L. Adamek,¹⁶⁴ J. Adelman,¹¹⁹ M. Adersberger,¹¹² A. Adiguzel,^{12c,c} T. Adye,¹⁴¹ A. A. Affolder,¹⁴³ Y. Afik,¹⁵⁷ C. Agheorghiesei,^{27c} J. A. Aguilar-Saavedra,^{137f,137a,d} F. Ahmadov,^{77,e} G. Aielli,^{71a,71b} S. Akatsuka,⁸³ T. P. A. Åkesson,⁹⁴ E. Akilli,⁵² A. V. Akimov,¹⁰⁸ G. L. Alberghi,^{23b,23a} J. Albert,¹⁷³ P. Albicocco,⁴⁹ M. J. Alconada Verzini,⁸⁶ S. Alderweireldt,¹¹⁷ M. Aleksa,³⁵ I. N. Aleksandrov,⁷⁷ C. Alexa,^{27b} D. Alexandre,¹⁹ T. Alexopoulos,¹⁰ M. Alhroob,¹²⁵ B. Ali,¹³⁹ G. Alimonti,^{66a} J. Alison,³⁶ S. P. Alkire,¹⁴⁵ C. Allaire,¹²⁹ B. M. M. Allbrooke,¹⁵³

B. W. Allen,¹²⁸ P. P. Allport,²¹ A. Aloisio,^{67a,67b} A. Alonso,³⁹ F. Alonso,⁸⁶ C. Alpigiani,¹⁴⁵ A. A. Alshehri,⁵⁵ M. I. Alstady,⁹⁹ B. Alvarez Gonzalez,³⁵ D. Álvarez Piqueras,¹⁷¹ M. G. Alviggi,^{67a,67b} B. T. Amadio,¹⁸ Y. Amaral Coutinho,^{78b} A. Ambler,¹⁰¹ L. Ambroz,¹³² C. Amelung,²⁶ D. Amidei,¹⁰³ S. P. Amor Dos Santos,^{137a,137c} S. Amoroso,⁴⁴ C. S. Amrouche,⁵² F. An,⁷⁶ C. Anastopoulos,¹⁴⁶ L. S. Ancu,⁵² N. Andari,¹⁴² T. Andeen,¹¹ C. F. Anders,^{59b} J. K. Anders,²⁰ K. J. Anderson,³⁶ A. Andreazza,^{66a,66b} V. Andrei,^{59a} C. R. Anelli,¹⁷³ S. Angelidakis,³⁷ I. Angelozzi,¹¹⁸ A. Angerami,³⁸ A. V. Anisenkov,^{120b,120a} A. Annovi,^{69a} C. Antel,^{59a} M. T. Anthony,¹⁴⁶ M. Antonelli,⁴⁹ D. J. A. Antrim,¹⁶⁸ F. Anulli,^{70a} M. Aoki,⁷⁹ J. A. Aparisi Pozo,¹⁷¹ L. Aperio Bella,³⁵ G. Arabidze,¹⁰⁴ J. P. Araque,^{137a} V. Araujo Ferraz,^{78b} R. Araujo Pereira,^{78b} A. T. H. Arce,⁴⁷ R. E. Ardeli,⁹¹ F. A. Arduh,⁸⁶ J-F. Arguin,¹⁰⁷ S. Argyropoulos,⁷⁵ J.-H. Arling,⁴⁴ A. J. Armbruster,³⁵ L. J. Armitage,⁹⁰ A. Armstrong,¹⁶⁸ O. Arnaez,¹⁶⁴ H. Arnold,¹¹⁸ M. Arratia,³¹ O. Arslan,²⁴ A. Artamonov,^{109a} G. Artoni,¹³² S. Artz,⁹⁷ S. Asai,¹⁶⁰ N. Asbah,⁵⁷ E. M. Asimakopoulou,¹⁶⁹ L. Asquith,¹⁵³ K. Assamagan,²⁹ R. Astalos,^{28a} R. J. Atkin,^{32a} M. Atkinson,¹⁷⁰ N. B. Atlay,¹⁴⁸ K. Augsten,¹³⁹ G. Avolio,³⁵ R. Avramidou,^{58a} M. K. Ayoub,^{15a} A. M. Azoulay,^{165b} G. Azuelos,^{107f} A. E. Baas,^{59a} M. J. Baca,²¹ H. Bachacou,¹⁴² K. Bachas,^{65a,65b} M. Backes,¹³² P. Bagnaia,^{70a,70b} M. Bahmani,⁸² H. Bahrsemani,¹⁴⁹ A. J. Bailey,¹⁷¹ V. R. Bailey,¹⁷⁰ J. T. Baines,¹⁴¹ M. Bajic,³⁹ C. Bakalis,¹⁰ O. K. Baker,¹⁸⁰ P. J. Bakker,¹¹⁸ D. Bakshi Gupta,⁸ S. Balaji,¹⁵⁴ E. M. Baldin,^{120b,120a} P. Balek,¹⁷⁷ F. Balli,¹⁴² W. K. Balunas,¹³⁴ J. Balz,⁹⁷ E. Banas,⁸² A. Bandyopadhyay,²⁴ S. Banerjee,^{178g} A. A. E. Bannoura,¹⁷⁹ L. Barak,¹⁵⁸ W. M. Barbe,³⁷ E. L. Barberio,¹⁰² D. Barberis,^{53b,53a} M. Barbero,⁹⁹ T. Barillari,¹¹³ M-S. Barisits,³⁵ J. Barkeloo,¹²⁸ T. Barklow,¹⁵⁰ R. Barnea,¹⁵⁷ S. L. Barnes,^{58c} B. M. Barnett,¹⁴¹ R. M. Barnett,¹⁸ Z. Barnovska-Blenessy,^{58a} A. Baroncelli,^{72a} G. Barone,²⁹ A. J. Barr,¹³² L. Barranco Navarro,¹⁷¹ F. Barreiro,⁹⁶ J. Barreiro Guimarães da Costa,^{15a} R. Bartoldus,¹⁵⁰ A. E. Barton,⁸⁷ P. Bartos,^{28a} A. Basalaez,¹³⁵ A. Bassalat,¹²⁹ R. L. Bates,⁵⁵ S. J. Batista,¹⁶⁴ S. Batlamous,^{34e} J. R. Batley,³¹ M. Battaglia,¹⁴³ M. Bause,^{70a,70b} F. Bauer,¹⁴² K. T. Bauer,¹⁶⁸ H. S. Bawa,¹⁵⁰ J. B. Beacham,¹²³ T. Beau,¹³³ P. H. Beauchemin,¹⁶⁷ P. Bechtel,²⁴ H. C. Beck,⁵¹ H. P. Beck,^{20h} K. Becker,⁵⁰ M. Becker,⁹⁷ C. Becot,⁴⁴ A. Beddall,^{12d} A. J. Beddall,^{12a} V. A. Bednyakov,⁷⁷ M. Bedognetti,¹¹⁸ C. P. Bee,¹⁵² T. A. Beermann,⁷⁴ M. Begalli,^{78b} M. Begel,²⁹ A. Behera,¹⁵² J. K. Behr,⁴⁴ F. Beisiegel,²⁴ A. S. Bell,⁹² G. Bella,¹⁵⁸ L. Bellagamba,^{23b} A. Bellerive,³³ M. Bellomo,¹⁵⁷ P. Bellos,⁹ K. Belotskiy,¹¹⁰ N. L. Belyaev,¹¹⁰ O. Benary,^{158a} D. Benchekrone,^{34a} M. Bender,¹¹² N. Benekos,¹⁰ Y. Benhammou,¹⁵⁸ E. Benhar Noccioli,¹⁸⁰ J. Benitez,⁷⁵ D. P. Benjamin,⁶ M. Benoit,⁵² J. R. Bensinger,²⁶ S. Bentvelsen,¹¹⁸ L. Beresford,¹³² M. Beretta,⁴⁹ D. Berge,⁴⁴ E. Bergeas Kuutmann,¹⁶⁹ N. Berger,⁵ B. Bergmann,¹³⁹ L. J. Bergsten,²⁶ J. Beringer,¹⁸ S. Berlendis,⁷ N. R. Bernard,¹⁰⁰ G. Bernardi,¹³³ C. Bernius,¹⁵⁰ F. U. Bernlochner,²⁴ T. Berry,⁹¹ P. Berta,⁹⁷ C. Bertella,^{15a} G. Bertoli,^{43a,43b} I. A. Bertram,⁸⁷ G. J. Besjes,³⁹ O. Bessidskaia Bylund,¹⁷⁹ M. Bessner,⁴⁴ N. Besson,¹⁴² A. Bethani,⁹⁸ S. Bethke,¹¹³ A. Betti,²⁴ A. J. Bevan,⁹⁰ J. Beyer,¹¹³ R. Bi,¹³⁶ R. M. Bianchi,¹³⁶ O. Biebel,¹¹² D. Biedermann,¹⁹ R. Bielski,³⁵ K. Bierwagen,⁹⁷ N. V. Biesuz,^{69a,69b} M. Biglietti,^{72a} T. R. V. Billoud,¹⁰⁷ M. Bindi,⁵¹ A. Bingul,^{12d} C. Bini,^{70a,70b} S. Biondi,^{23b,23a} M. Birman,¹⁷⁷ T. Bisanz,⁵¹ J. P. Biswal,¹⁵⁸ C. Bittrich,⁴⁶ D. M. Bjergaard,⁴⁷ J. E. Black,¹⁵⁰ K. M. Black,²⁵ T. Blazek,^{28a} I. Bloch,⁴⁴ C. Blocker,²⁶ A. Blue,⁵⁵ U. Blumenschein,⁹⁰ Dr. Blunier,^{144a} G. J. Bobbink,¹¹⁸ V. S. Bobrovnikov,^{120b,120a} S. S. Bocchetta,⁹⁴ A. Bocci,⁴⁷ D. Boerner,¹⁷⁹ D. Bogavac,¹¹² A. G. Bogdanchikov,^{120b,120a} C. Bohm,^{43a} V. Boisvert,⁹¹ P. Bokan,^{51,169} T. Bold,^{81a} A. S. Boldyrev,¹¹¹ A. E. Bolz,^{59b} M. Bomben,¹³³ M. Bona,⁹⁰ J. S. Bonilla,¹²⁸ M. Boonekamp,¹⁴² H. M. Borecka-Bielska,⁸⁸ A. Borisov,¹²¹ G. Borissoy,⁸⁷ J. Bortfeldt,³⁵ D. Bortoletto,¹³² V. Bortolotto,^{71a,71b} D. Boscherini,^{23b} M. Bosman,¹⁴ J. D. Bossio Sola,³⁰ K. Bouaouda,^{34a} J. Boudreau,¹³⁶ E. V. Bouhova-Thacker,⁸⁷ D. Boumediene,³⁷ C. Bourdarios,¹²⁹ S. K. Boutle,⁵⁵ A. Boveia,¹²³ J. Boyd,³⁵ D. Boye,^{32b} I. R. Boyko,⁷⁷ A. J. Bozson,⁹¹ J. Bracinik,²¹ N. Brahimi,⁹⁹ A. Brandt,⁸ G. Brandt,¹⁷⁹ O. Brandt,^{59a} F. Braren,⁴⁴ U. Bratzler,¹⁶¹ B. Brau,¹⁰⁰ J. E. Brau,¹²⁸ W. D. Breaden Madden,⁵⁵ K. Brendlinger,⁴⁴ L. Brenner,⁴⁴ R. Brenner,¹⁶⁹ S. Bressler,¹⁷⁷ B. Brickwedde,⁹⁷ D. L. Briglin,²¹ D. Britton,⁵⁵ D. Britzger,¹¹³ I. Brock,²⁴ R. Brock,¹⁰⁴ G. Brooijmans,³⁸ T. Brooks,⁹¹ W. K. Brooks,^{144b} E. Brost,¹¹⁹ J. H. Broughton,²¹ P. A. Bruckman de Renstrom,⁸² D. Bruncko,^{28b} A. Bruni,^{23b} G. Bruni,^{23b} L. S. Bruni,¹¹⁸ S. Bruno,^{71a,71b} B. H. Brunt,³¹ M. Bruschi,^{23b} N. Bruscino,¹³⁶ P. Bryant,³⁶ L. Bryngemark,⁹⁴ T. Buanes,¹⁷ Q. Buat,³⁵ P. Buchholz,¹⁴⁸ A. G. Buckley,⁵⁵ I. A. Budagov,⁷⁷ M. K. Bugge,¹³¹ F. Bühner,⁵⁰ O. Bulekov,¹¹⁰ D. Bullock,⁸ T. J. Burch,¹¹⁹ S. Burdin,⁸⁸ C. D. Burgard,¹¹⁸ A. M. Burger,⁵ B. Burghgrave,¹¹⁹ K. Burka,⁸² S. Burke,¹⁴¹ I. Burmeister,⁴⁵ J. T. P. Burr,¹³² V. Büscher,⁹⁷ E. Buschmann,⁵¹ P. Bussey,⁵⁵ J. M. Butler,²⁵ C. M. Buttar,⁵⁵ J. M. Butterworth,⁹² P. Butti,³⁵ W. Buttinger,³⁵ A. Buzatu,¹⁵⁵ A. R. Buzykaev,^{120b,120a} G. Cabras,^{23b,23a} S. Cabrera Urbán,¹⁷¹ D. Caforio,¹³⁹ H. Cai,¹⁷⁰ V. M. M. Cairo,² O. Cakir,^{4a} N. Calace,³⁵ P. Calafiura,¹⁸ A. Calandri,⁹⁹ G. Calderini,¹³³ P. Calfayan,⁶³ G. Callea,⁵⁵ L. P. Caloba,^{78b} S. Calvente Lopez,⁹⁶ D. Calvet,³⁷ S. Calvet,³⁷ T. P. Calvet,¹⁵² M. Calvetti,^{69a,69b} R. Camacho Toro,¹³³ S. Camarda,³⁵ D. Camarero Munoz,⁹⁶ P. Camarri,^{71a,71b} D. Cameron,¹³¹ R. Caminal Armadans,¹⁰⁰ C. Camincher,³⁵ S. Campana,³⁵ M. Campanelli,⁹² A. Camplani,³⁹ A. Campoverde,¹⁴⁸

V. Canale,^{67a,67b} M. Cano Bret,^{58c} J. Cantero,¹²⁶ T. Cao,¹⁵⁸ Y. Cao,¹⁷⁰ M. D. M. Capeans Garrido,³⁵ I. Caprini,^{27b} M. Caprini,^{27b} M. Capua,^{40b,40a} R. M. Carbone,³⁸ R. Cardarelli,^{71a} F. C. Cardillo,¹⁴⁶ I. Carli,¹⁴⁰ T. Carli,³⁵ G. Carlino,^{67a} B. T. Carlson,¹³⁶ L. Carminati,^{66a,66b} R. M. D. Carney,^{43a,43b} S. Caron,¹¹⁷ E. Carquin,^{144b} S. Carrà,^{66a,66b} J. W. S. Carter,¹⁶⁴ D. Casadei,^{32b} M. P. Casado,^{14,i} A. F. Casha,¹⁶⁴ D. W. Casper,¹⁶⁸ R. Castelijns,¹¹⁸ F. L. Castillo,¹⁷¹ V. Castillo Gimenez,¹⁷¹ N. F. Castro,^{137a,137e} A. Catinaccio,³⁵ J. R. Catmore,¹³¹ A. Cattai,³⁵ J. Caudron,²⁴ V. Cavaliere,²⁹ E. Cavallaro,¹⁴ D. Cavalli,^{66a} M. Cavalli-Sforza,¹⁴ V. Cavasinni,^{69a,69b} E. Celebi,^{12b} F. Ceradini,^{72a,72b} L. Cerda Alberich,¹⁷¹ A. S. Cerqueira,^{78a} A. Cerri,¹⁵³ L. Cerrito,^{71a,71b} F. Cerutti,¹⁸ A. Cervelli,^{23b,23a} S. A. Cetin,^{12b} A. Chafaq,^{34a} D. Chakraborty,¹¹⁹ S. K. Chan,⁵⁷ W. S. Chan,¹¹⁸ W. Y. Chan,⁸⁸ J. D. Chapman,³¹ B. Chargeishvili,^{156b} D. G. Charlton,²¹ C. C. Chau,³³ C. A. Chavez Barajas,¹⁵³ S. Che,¹²³ A. Chegwidden,¹⁰⁴ S. Chekanov,⁶ S. V. Chekulaev,^{165a} G. A. Chelkov,^{77,j} M. A. Chelstowska,³⁵ B. Chen,⁷⁶ C. Chen,^{58a} C. H. Chen,⁷⁶ H. Chen,²⁹ J. Chen,^{58a} J. Chen,³⁸ S. Chen,¹³⁴ S. J. Chen,^{15c} X. Chen,^{15b,k} Y. Chen,⁸⁰ Y.-H. Chen,⁴⁴ H. C. Cheng,^{61a} H. J. Cheng,^{15d} A. Cheplakov,⁷⁷ E. Cheremushkina,¹²¹ R. Cherkaoui El Moursli,^{34e} E. Cheu,⁷ K. Cheung,⁶² T. J. A. Chevaléras,¹⁴² L. Chevalier,¹⁴² V. Chiarella,⁴⁹ G. Chiarelli,^{69a} G. Chiodini,^{65a} A. S. Chisholm,^{35,21} A. Chitan,^{27b} I. Chiu,¹⁶⁰ Y. H. Chiu,¹⁷³ M. V. Chizhov,⁷⁷ K. Choi,⁶³ A. R. Chomont,¹²⁹ S. Chouridou,¹⁵⁹ Y. S. Chow,¹¹⁸ V. Christodoulou,⁹² M. C. Chu,^{61a} J. Chudoba,¹³⁸ A. J. Chuinard,¹⁰¹ J. J. Chwastowski,⁸² L. Chytka,¹²⁷ D. Cinca,⁴⁵ V. Cindro,⁸⁹ I. A. Cioară,²⁴ A. Ciochio,¹⁸ F. Ciotto,^{67a,67b} Z. H. Citron,¹⁷⁷ M. Citterio,^{66a} A. Clark,⁵² M. R. Clark,³⁸ P. J. Clark,⁴⁸ C. Clement,^{43a,43b} Y. Coadou,⁹⁹ M. Cobal,^{64a,64c} A. Coccaro,^{53b,53a} J. Cochran,⁷⁶ H. Cohen,¹⁵⁸ A. E. C. Coimbra,¹⁷⁷ L. Colasurdo,¹¹⁷ B. Cole,³⁸ A. P. Colijn,¹¹⁸ J. Collot,⁵⁶ P. Conde Muino,^{137a,l} E. Coniavitis,⁵⁰ S. H. Connell,^{32b} I. A. Connelly,⁹⁸ S. Constantinescu,^{27b} F. Conventi,^{67a,m} A. M. Cooper-Sarkar,¹³² F. Cormier,¹⁷² K. J. R. Cormier,¹⁶⁴ L. D. Corpe,⁹² M. Corradi,^{70a,70b} E. E. Corrigan,⁹⁴ F. Corriveau,^{101,n} A. Cortes-Gonzalez,³⁵ M. J. Costa,¹⁷¹ F. Costanza,⁵ D. Costanzo,¹⁴⁶ G. Cottin,³¹ G. Cowan,⁹¹ J. W. Cowley,³¹ B. E. Cox,⁹⁸ J. Crane,⁹⁸ K. Cranmer,¹²² S. J. Crawley,⁵⁵ R. A. Creager,¹³⁴ G. Cree,³³ S. Crépe-Renaudin,⁵⁶ F. Crescioli,¹³³ M. Cristinziani,²⁴ V. Croft,¹²² G. Crosetti,^{40b,40a} A. Cueto,⁹⁶ T. Cuhadar Donszelmann,¹⁴⁶ A. R. Cukierman,¹⁵⁰ S. Czekierda,⁸² P. Czodrowski,³⁵ M. J. Da Cunha Sargedas De Sousa,^{58b} C. Da Via,⁹⁸ W. Dabrowski,^{81a} T. Dado,^{28a,o} S. Dahbi,^{34e} T. Dai,¹⁰³ F. Dallaire,¹⁰⁷ C. Dallapiccola,¹⁰⁰ M. Dam,³⁹ G. D'amen,^{23b,23a} J. Damp,⁹⁷ J. R. Dandoy,¹³⁴ M. F. Daneri,³⁰ N. P. Dang,^{178,g} N. D. Dann,⁹⁸ M. Danninger,¹⁷² V. Dao,³⁵ G. Darbo,^{53b} S. Darmora,⁸ O. Dartsis,⁵ A. Dattagupta,¹²⁸ T. Daubney,⁴⁴ S. D'Auria,^{66a,66b} W. Davey,²⁴ C. David,⁴⁴ T. Davidek,¹⁴⁰ D. R. Davis,⁴⁷ E. Dawe,¹⁰² I. Dawson,¹⁴⁶ K. De,⁸ R. De Asmundis,^{67a} A. De Benedetti,¹²⁵ M. De Beurs,¹¹⁸ S. De Castro,^{23b,23a} S. De Cecco,^{70a,70b} N. De Groot,¹¹⁷ P. de Jong,¹¹⁸ H. De la Torre,¹⁰⁴ F. De Lorenzi,⁷⁶ A. De Maria,^{69a,69b} D. De Pedis,^{70a} A. De Salvo,^{70a} U. De Sanctis,^{71a,71b} M. De Santis,^{71a,71b} A. De Santo,¹⁵³ K. De Vasconcelos Corga,⁹⁹ J. B. De Vivie De Regie,¹²⁹ C. Debenedetti,¹⁴³ D. V. Dedovich,⁷⁷ N. Dehghanian,³ M. Del Gaudio,^{40b,40a} J. Del Peso,⁹⁶ Y. Delabat Diaz,⁴⁴ D. Delgove,¹²⁹ F. Deliot,¹⁴² C. M. Delitzsch,⁷ M. Della Pietra,^{67a,67b} D. Della Volpe,⁵² A. Dell'Acqua,³⁵ L. Dell'Asta,²⁵ M. Delmastro,⁵ C. Delporte,¹²⁹ P. A. Delsart,⁵⁶ D. A. DeMarco,¹⁶⁴ S. Demers,¹⁸⁰ M. Demichev,⁷⁷ S. P. Denisov,¹²¹ D. Denysiuk,¹¹⁸ L. D'Eramo,¹³³ D. Derendarz,⁸² J. E. Derkaoui,^{34d} F. Derue,¹³³ P. Dervan,⁸⁸ K. Desch,²⁴ C. Deterre,⁴⁴ K. Dette,¹⁶⁴ M. R. Devesa,³⁰ P. O. Deviveiros,³⁵ A. Dewhurst,¹⁴¹ S. Dhaliwal,²⁶ F. A. Di Bello,⁵² A. Di Ciaccio,^{71a,71b} L. Di Ciaccio,⁵ W. K. Di Clemente,¹³⁴ C. Di Donato,^{67a,67b} A. Di Girolamo,³⁵ G. Di Gregorio,^{69a,69b} B. Di Micco,^{72a,72b} R. Di Nardo,¹⁰⁰ K. F. Di Petrillo,⁵⁷ R. Di Sipio,¹⁶⁴ D. Di Valentino,³³ C. Diaconu,⁹⁹ M. Diamond,¹⁶⁴ F. A. Dias,³⁹ T. Dias Do Vale,^{137a} M. A. Diaz,^{144a} J. Dickinson,¹⁸ E. B. Diehl,¹⁰³ J. Dietrich,¹⁹ S. Díez Cornell,⁴⁴ A. Dimitrievska,¹⁸ J. Dingfelder,²⁴ F. Dittus,³⁵ F. Djama,⁹⁹ T. Djobava,^{156b} J. I. Djuvsland,¹⁷ M. A. B. Do Vale,^{78c} M. Dobre,^{27b} D. Dodsworth,²⁶ C. Doglioni,⁹⁴ J. Dolejsi,¹⁴⁰ Z. Dolezal,¹⁴⁰ M. Donadelli,^{78d} J. Donini,³⁷ A. D'onofrio,⁹⁰ M. D'onofrio,⁸⁸ J. Dopke,¹⁴¹ A. Doria,^{67a} M. T. Dova,⁸⁶ A. T. Doyle,⁵⁵ E. Drechsler,¹⁴⁹ E. Dreyer,¹⁴⁹ T. Dreyer,⁵¹ Y. Du,^{58b} F. Dubinin,¹⁰⁸ M. Dubovsky,^{28a} A. Dubreuil,⁵² E. Duchovni,¹⁷⁷ G. Duckeck,¹¹² A. Ducourthial,¹³³ O. A. Ducu,^{107,p} D. Duda,¹¹³ A. Dudarev,³⁵ A. C. Dudder,⁹⁷ E. M. Duffield,¹⁸ L. Duflot,¹²⁹ M. Dührssen,³⁵ C. Dülsen,¹⁷⁹ M. Dumancic,¹⁷⁷ A. E. Dumitriu,^{27b,q} A. K. Duncan,⁵⁵ M. Dunford,^{59a} A. Duperrin,⁹⁹ H. Duran Yildiz,^{4a} M. Düren,⁵⁴ A. Durglishvili,^{156b} D. Duschinger,⁴⁶ B. Dutta,⁴⁴ D. Duvnjak,¹ M. Dyndal,⁴⁴ S. Dysch,⁹⁸ B. S. Dziedzic,⁸² K. M. Ecker,¹¹³ R. C. Edgar,¹⁰³ T. Eifert,³⁵ G. Eigen,¹⁷ K. Einsweiler,¹⁸ T. Ekelof,¹⁶⁹ M. El Kacimi,^{34c} R. El Kosseifi,⁹⁹ V. Ellajosyula,⁹⁹ M. Ellert,¹⁶⁹ F. Ellinghaus,¹⁷⁹ A. A. Elliot,⁹⁰ N. Ellis,³⁵ J. Elmsheuser,²⁹ M. Elsing,³⁵ D. Emeliyanov,¹⁴¹ A. Emerman,³⁸ Y. Enari,¹⁶⁰ J. S. Ennis,¹⁷⁵ M. B. Epland,⁴⁷ J. Erdmann,⁴⁵ A. Ereditato,²⁰ S. Errede,¹⁷⁰ M. Escalier,¹²⁹ C. Escobar,¹⁷¹ O. Estrada Pastor,¹⁷¹ A. I. Etiennev,¹⁴² E. Etzion,¹⁵⁸ H. Evans,⁶³ A. Ezhilov,¹³⁵ M. Ezzi,^{34e} F. Fabbri,⁵⁵ L. Fabbri,^{23b,23a} V. Fabiani,¹¹⁷ G. Facini,⁹² R. M. Faisca Rodrigues Pereira,^{137a} R. M. Fakhrutdinov,¹²¹ S. Falciano,^{70a} P. J. Falke,⁵ S. Falke,⁵ J. Faltova,¹⁴⁰ Y. Fang,^{15a}

- M. Fanti,^{66a,66b} A. Farbin,⁸ A. Farilla,^{72a} E. M. Farina,^{68a,68b} T. Farooque,¹⁰⁴ S. Farrell,¹⁸ S. M. Farrington,¹⁷⁵ P. Farthouat,³⁵
 F. Fassi,^{34e} P. Fassnacht,³⁵ D. Fassouliotis,⁹ M. Fauci Giannelli,⁴⁸ A. Favareto,^{53b,53a} W. J. Fawcett,³¹ L. Fayard,¹²⁹
 O. L. Fedin,^{135,r} W. Fedorko,¹⁷² M. Feickert,⁴¹ S. Feigl,¹³¹ L. Feligioni,⁹⁹ C. Feng,^{58b} E. J. Feng,³⁵ M. Feng,⁴⁷ M. J. Fenton,⁵⁵
 A. B. Fenyuk,¹²¹ L. Feremenga,⁸ J. Ferrando,⁴⁴ A. Ferrari,¹⁶⁹ P. Ferrari,¹¹⁸ R. Ferrari,^{68a} D. E. Ferreira de Lima,^{59b}
 A. Ferrer,¹⁷¹ D. Ferrere,⁵² C. Ferretti,¹⁰³ F. Fiedler,⁹⁷ A. Filipčić,⁸⁹ F. Filthaut,¹¹⁷ K. D. Finelli,²⁵ M. C. N. Fiolhais,^{137a,137c,s}
 L. Fiorini,¹⁷¹ C. Fischer,¹⁴ W. C. Fisher,¹⁰⁴ N. Flaschel,⁴⁴ I. Fleck,¹⁴⁸ P. Fleischmann,¹⁰³ R. R. M. Fletcher,¹³⁴ T. Flick,¹⁷⁹
 B. M. Flierl,¹¹² L. M. Flores,¹³⁴ L. R. Flores Castillo,^{61a} F. M. Follega,^{73a,73b} N. Fomin,¹⁷ G. T. Forcolin,^{73a,73b} A. Formica,¹⁴²
 F. A. Förster,¹⁴ A. C. Forti,⁹⁸ A. G. Foster,²¹ D. Fournier,¹²⁹ H. Fox,⁸⁷ S. Fracchia,¹⁴⁶ P. Francavilla,^{69a,69b} M. Franchini,^{23b,23a}
 S. Franchino,^{59a} D. Francis,³⁵ L. Franconi,¹⁴³ M. Franklin,⁵⁷ M. Frate,¹⁶⁸ M. Fraternali,^{68a,68b} A. N. Fray,⁹⁰ D. Freeborn,⁹²
 B. Freund,¹⁰⁷ W. S. Freund,^{78b} E. M. Freundlich,⁴⁵ D. C. Frizzell,¹²⁵ D. Froidevaux,³⁵ J. A. Frost,¹³² C. Fukunaga,¹⁶¹
 E. Fullana Torregrosa,¹⁷¹ E. Fumagalli,^{53b,53a} T. Fusayasu,¹¹⁴ J. Fuster,¹⁷¹ O. Gabizon,¹⁵⁷ A. Gabrielli,^{23b,23a} A. Gabrielli,¹⁸
 G. P. Gach,^{81a} S. Gadatsch,⁵² P. Gadow,¹¹³ G. Gagliardi,^{53b,53a} L. G. Gagnon,¹⁰⁷ C. Galea,^{27b} B. Galhardo,^{137a,137c}
 E. J. Gallas,¹³² B. J. Gallop,¹⁴¹ P. Gallus,¹³⁹ G. Galster,³⁹ R. Gamboa Goni,⁹⁰ K. K. Gan,¹²³ S. Ganguly,¹⁷⁷ J. Gao,^{58a}
 Y. Gao,⁸⁸ Y. S. Gao,^{150,t} C. García,¹⁷¹ J. E. García Navarro,¹⁷¹ J. A. García Pascual,^{15a} M. Garcia-Sciveres,¹⁸
 R. W. Gardner,³⁶ N. Garelli,¹⁵⁰ S. Gargiulo,⁵⁰ V. Garonne,¹³¹ K. Gasnikova,⁴⁴ A. Gaudiello,^{53b,53a} G. Gaudio,^{68a}
 I. L. Gavrilenko,¹⁰⁸ A. Gavrilyuk,¹⁰⁹ C. Gay,¹⁷² G. Gaycken,²⁴ E. N. Gazis,¹⁰ C. N. P. Gee,¹⁴¹ J. Geisen,⁵¹ M. Geisen,⁹⁷
 M. P. Geisler,^{59a} C. Gemme,^{53b} M. H. Genest,⁵⁶ C. Geng,¹⁰³ S. Gentile,^{70a,70b} S. George,⁹¹ D. Gerbaudo,¹⁴ G. Gessner,⁴⁵
 S. Ghasemi,¹⁴⁸ M. Ghasemi Bostanabad,¹⁷³ M. Ghneimat,²⁴ B. Giacobbe,^{23b} S. Giagu,^{70a,70b} N. Giangiacomi,^{23b,23a}
 P. Giannetti,^{69a} A. Giannini,^{67a,67b} S. M. Gibson,⁹¹ M. Gignac,¹⁴³ D. Gillberg,³³ G. Gilles,¹⁷⁹ D. M. Gingrich,^{3,f}
 M. P. Giordani,^{64a,64c} F. M. Giorgi,^{23b} P. F. Giraud,¹⁴² P. Giromini,⁵⁷ G. Giugliarelli,^{64a,64c} D. Giugni,^{66a} F. Giuli,¹³²
 M. Giulini,^{59b} S. Gkaitatzis,¹⁵⁹ I. Gkialas,^{9,u} E. L. Gkougkousis,¹⁴ P. Gkoutoumis,¹⁰ L. K. Gladilin,¹¹¹ C. Glasman,⁹⁶
 J. Glatzer,¹⁴ P. C. F. Glaysheer,⁴⁴ A. Glazov,⁴⁴ M. Goblirsch-Kolb,²⁶ J. Godlewski,⁸² S. Goldfarb,¹⁰² T. Golling,⁵²
 D. Golubkov,¹²¹ A. Gomes,^{137a,137b} R. Goncalves Gama,⁵¹ R. Gonçalves,^{137a} G. Gonella,⁵⁰ L. Gonella,²¹ A. Gongadze,⁷⁷
 F. Gonnella,²¹ J. L. Gonski,⁵⁷ S. González de la Hoz,¹⁷¹ S. Gonzalez-Sevilla,⁵² L. Goossens,³⁵ P. A. Gorbounov,¹⁰⁹
 H. A. Gordon,²⁹ B. Gorini,³⁵ E. Gorini,^{65a,65b} A. Gorišek,⁸⁹ A. T. Goshaw,⁴⁷ C. Gössling,⁴⁵ M. I. Gostkin,⁷⁷ C. A. Gottardo,²⁴
 C. R. Goudet,¹²⁹ D. Goujdami,^{34c} A. G. Goussiou,¹⁴⁵ N. Govender,^{32b,v} C. Goy,⁵ E. Gozani,¹⁵⁷ I. Grabowska-Bold,^{81a}
 P. O. J. Gradin,¹⁶⁹ E. C. Graham,⁸⁸ J. Gramling,¹⁶⁸ E. Gramstad,¹³¹ S. Grancagnolo,¹⁹ V. Gratchev,¹³⁵ P. M. Gravila,^{27f}
 F. G. Gravili,^{65a,65b} C. Gray,⁵⁵ H. M. Gray,¹⁸ Z. D. Greenwood,^{93,w} C. Greife,²⁴ K. Gregersen,⁹⁴ I. M. Gregor,⁴⁴ P. Grenier,¹⁵⁰
 K. Grevtsov,⁴⁴ N. A. Grieser,¹²⁵ J. Griffiths,⁸ A. A. Grillo,¹⁴³ K. Grimm,^{150,x} S. Grinstein,^{14,y} Ph. Gris,³⁷ J.-F. Grivaz,¹²⁹
 S. Groh,⁹⁷ E. Gross,¹⁷⁷ J. Grosse-Knetter,⁵¹ G. C. Grossi,⁹³ Z. J. Grout,⁹² C. Grud,¹⁰³ A. Grummer,¹¹⁶ L. Guan,¹⁰³
 W. Guan,¹⁷⁸ J. Guenther,³⁵ A. Guerguichon,¹²⁹ F. Guescini,^{165a} D. Guest,¹⁶⁸ R. Gugel,⁵⁰ B. Gui,¹²³ T. Guillemin,⁵
 S. Guindon,³⁵ U. Gul,⁵⁵ J. Guo,^{58c} W. Guo,¹⁰³ Y. Guo,^{58a,z} Z. Guo,⁹⁹ R. Gupta,⁴⁴ S. Gurbuz,^{12c} G. Gustavino,¹²⁵
 P. Gutierrez,¹²⁵ C. Gutsche,⁹² C. Guyot,¹⁴² M. P. Guzik,^{81a} C. Gwenlan,¹³² C. B. Gwilliam,⁸⁸ A. Haas,¹²² C. Haber,¹⁸
 H. K. Hadavand,⁸ N. Haddad,^{34e} A. Hadeef,^{58a} S. Hageböck,²⁴ M. Hagihara,¹⁶⁶ H. Hakobyan,^{181,a} M. Haleem,¹⁷⁴ J. Haley,¹²⁶
 G. Halladjian,¹⁰⁴ G. D. Hallewell,⁹⁹ K. Hamacher,¹⁷⁹ P. Hamal,¹²⁷ K. Hamano,¹⁷³ A. Hamilton,^{32a} G. N. Hamity,¹⁴⁶
 K. Han,^{58a,aa} L. Han,^{58a} S. Han,^{15d} K. Hanagaki,^{79,bb} M. Hance,¹⁴³ D. M. Handl,¹¹² B. Haney,¹³⁴ R. Hankache,¹³³ P. Hanke,^{59a}
 E. Hansen,⁹⁴ J. B. Hansen,³⁹ J. D. Hansen,³⁹ M. C. Hansen,²⁴ P. H. Hansen,³⁹ K. Hara,¹⁶⁶ A. S. Hard,¹⁷⁸ T. Harenberg,¹⁷⁹
 S. Harkusha,¹⁰⁵ P. F. Harrison,¹⁷⁵ N. M. Hartmann,¹¹² Y. Hasegawa,¹⁴⁷ A. Hasib,⁴⁸ S. Hassani,¹⁴² S. Haug,²⁰ R. Hauser,¹⁰⁴
 L. Hauswald,⁴⁶ L. B. Havener,³⁸ M. Havranek,¹³⁹ C. M. Hawkes,²¹ R. J. Hawkings,³⁵ D. Hayden,¹⁰⁴ C. Hayes,¹⁵²
 C. P. Hays,¹³² J. M. Hays,⁹⁰ H. S. Hayward,⁸⁸ S. J. Haywood,¹⁴¹ F. He,^{58a} M. P. Heath,⁴⁸ V. Hedberg,⁹⁴ L. Heelan,⁸ S. Heer,²⁴
 K. K. Heidegger,⁵⁰ J. Heilman,³³ S. Heim,⁴⁴ T. Heim,¹⁸ B. Heinemann,^{44,cc} J. J. Heinrich,¹¹² L. Heinrich,¹²² C. Heinz,⁵⁴
 J. Hejbal,¹³⁸ L. Helary,³⁵ A. Held,¹⁷² S. Hellesund,¹³¹ C. M. Helling,¹⁴³ S. Hellman,^{43a,43b} C. Helsens,³⁵
 R. C. W. Henderson,⁸⁷ Y. Heng,¹⁷⁸ S. Henkelmann,¹⁷² A. M. Henriques Correia,³⁵ G. H. Herbert,¹⁹ H. Herde,²⁶ V. Herget,¹⁷⁴
 Y. Hernández Jiménez,^{32c} H. Herr,⁹⁷ M. G. Herrmann,¹¹² T. Herrmann,⁴⁶ G. Herten,⁵⁰ R. Hertenberger,¹¹² L. Hervas,³⁵
 T. C. Herwig,¹³⁴ G. G. Hesketh,⁹² N. P. Hessey,^{165a} A. Higashida,¹⁶⁰ S. Higashino,⁷⁹ E. Higón-Rodríguez,¹⁷¹
 K. Hildebrand,³⁶ E. Hill,¹⁷³ J. C. Hill,³¹ K. K. Hill,²⁹ K. H. Hiller,⁴⁴ S. J. Hillier,²¹ M. Hils,⁴⁶ I. Hinchliffe,¹⁸
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 N. Hod,^{165a} M. C. Hodgkinson,¹⁴⁶ A. Hoecker,³⁵ M. R. Hoefkamp,¹¹⁶ F. Hoenig,¹¹² D. Hohn,⁵⁰ D. Hohov,¹²⁹
 T. R. Holmes,³⁶ M. Holzbock,¹¹² M. Homann,⁴⁵ B. H. Hommels,³¹ S. Honda,¹⁶⁶ T. Honda,⁷⁹ T. M. Hong,¹³⁶ A. Hönle,¹¹³

- B. H. Hooberman,¹⁷⁰ W. H. Hopkins,¹²⁸ Y. Horii,¹¹⁵ P. Horn,⁴⁶ A. J. Horton,¹⁴⁹ L. A. Horyn,³⁶ J.-Y. Hostachy,⁵⁶
A. Hostiuc,¹⁴⁵ S. Hou,¹⁵⁵ A. Houmada,^{34a} J. Howarth,⁹⁸ J. Hoya,⁸⁶ M. Hrabovsky,¹²⁷ I. Hristova,¹⁹ J. Hrivnac,¹²⁹
A. Hrynevich,¹⁰⁶ T. Hryn'ova,⁵ P. J. Hsu,⁶² S.-C. Hsu,¹⁴⁵ Q. Hu,²⁹ S. Hu,^{58c} Y. Huang,^{15a} Z. Hubacek,¹³⁹ F. Hubaut,⁹⁹
M. Huebner,²⁴ F. Huegging,²⁴ T. B. Huffman,¹³² M. Huhtinen,³⁵ R. F. H. Hunter,³³ P. Huo,¹⁵² A. M. Hupe,³³
N. Huseynov,^{77,e} J. Huston,¹⁰⁴ J. Huth,⁵⁷ R. Hyneman,¹⁰³ G. Iacobucci,⁵² G. Iakovidis,²⁹ I. Ibragimov,¹⁴⁸
L. Iconomidou-Fayard,¹²⁹ Z. Idrissi,^{34e} P. Iengo,³⁵ R. Ignazzi,³⁹ O. Igonkina,^{118,dd} R. Iguchi,¹⁶⁰ T. Iizawa,⁵² Y. Ikegami,⁷⁹
M. Ikeno,⁷⁹ D. Iliadis,¹⁵⁹ N. Ilic,¹¹⁷ F. Iltzsche,⁴⁶ G. Introzzi,^{68a,68b} M. Iodice,^{72a} K. Iordanidou,³⁸ V. Ippolito,^{70a,70b}
M. F. Isacson,¹⁶⁹ N. Ishijima,¹³⁰ M. Ishino,¹⁶⁰ M. Ishitsuka,¹⁶² W. Islam,¹²⁶ C. Issever,¹³² S. Istin,¹⁵⁷ F. Ito,¹⁶⁶
J. M. Iturbe Ponce,^{61a} R. Iuppa,^{73a,73b} A. Ivina,¹⁷⁷ H. Iwasaki,⁷⁹ J. M. Izen,⁴² V. Izzo,^{67a} P. Jacka,¹³⁸ P. Jackson,¹
R. M. Jacobs,²⁴ V. Jain,² G. Jäkel,¹⁷⁹ K. B. Jakobi,⁹⁷ K. Jakobs,⁵⁰ S. Jakobsen,⁷⁴ T. Jakoubek,¹³⁸ D. O. Jamin,¹²⁶ R. Jansky,⁵²
J. Janssen,²⁴ M. Janus,⁵¹ P. A. Janus,^{81a} G. Jarlskog,⁹⁴ N. Javadov,^{77,e} T. Javůrek,³⁵ M. Javurkova,⁵⁰ F. Jeanneau,¹⁴²
L. Jeanty,¹⁸ J. Jejelava,^{156a,ee} A. Jelinskas,¹⁷⁵ P. Jenni,^{50,ff} J. Jeong,⁴⁴ N. Jeong,⁴⁴ S. Jézéquel,⁵ H. Ji,¹⁷⁸ J. Jia,¹⁵² H. Jiang,⁷⁶
Y. Jiang,^{58a} Z. Jiang,^{150,gg} S. Jiggins,⁵⁰ F. A. Jimenez Morales,³⁷ J. Jimenez Pena,¹⁷¹ S. Jin,^{15c} A. Jinaru,^{27b} O. Jinnouchi,¹⁶²
H. Jivan,^{32c} P. Johansson,¹⁴⁶ K. A. Johns,⁷ C. A. Johnson,⁶³ K. Jon-And,^{43a,43b} R. W. L. Jones,⁸⁷ S. D. Jones,¹⁵³ S. Jones,⁷
T. J. Jones,⁸⁸ J. Jongmanns,^{59a} P. M. Jorge,^{137a,137b} J. Jovicevic,^{165a} X. Ju,¹⁸ J. J. Junggeburth,¹¹³ A. Juste Rozas,^{14,y}
A. Kaczmarska,⁸² M. Kado,¹²⁹ H. Kagan,¹²³ M. Kagan,¹⁵⁰ T. Kaji,¹⁷⁶ E. Kajomovitz,¹⁵⁷ C. W. Kalderon,⁹⁴ A. Kaluza,⁹⁷
S. Kama,⁴¹ A. Kamenshchikov,¹²¹ L. Kanjir,⁸⁹ Y. Kano,¹⁶⁰ V. A. Kantserov,¹¹⁰ J. Kanzaki,⁷⁹ L. S. Kaplan,¹⁷⁸ D. Kar,^{32c}
M. J. Kareem,^{165b} E. Karentzos,¹⁰ S. N. Karpov,⁷⁷ Z. M. Karpova,⁷⁷ V. Kartvelishvili,⁸⁷ A. N. Karyukhin,¹²¹ L. Kashif,¹⁷⁸
R. D. Kass,¹²³ A. Kastanas,^{43a,43b} Y. Kataoka,¹⁶⁰ C. Kato,^{58d,58c} J. Katzy,⁴⁴ K. Kawade,⁸⁰ K. Kawagoe,⁸⁵ T. Kawaguchi,¹¹⁵
T. Kawamoto,¹⁶⁰ G. Kawamura,⁵¹ E. F. Kay,⁸⁸ V. F. Kazanin,^{120b,120a} R. Keeler,¹⁷³ R. Kehoe,⁴¹ J. S. Keller,³³
E. Kellermann,⁹⁴ J. J. Kempster,²¹ J. Kendrick,²¹ O. Kepka,¹³⁸ S. Kersten,¹⁷⁹ B. P. Kerševan,⁸⁹ S. Ketabchi Haghighat,¹⁶⁴
R. A. Keyes,¹⁰¹ M. Khader,¹⁷⁰ F. Khalil-Zada,¹³ A. Khanov,¹²⁶ A. G. Kharlamov,^{120b,120a} T. Kharlamova,^{120b,120a}
E. E. Khoda,¹⁷² A. Khodinov,¹⁶³ T. J. Khoo,⁵² E. Khramov,⁷⁷ J. Khubua,^{156b} S. Kido,⁸⁰ M. Kiehn,⁵² C. R. Kilby,⁹¹
Y. K. Kim,³⁶ N. Kimura,^{64a,64c} O. M. Kind,¹⁹ B. T. King,⁸⁸ D. Kirchmeier,⁴⁶ J. Kirk,¹⁴¹ A. E. Kiryunin,¹¹³ T. Kishimoto,¹⁶⁰
D. Kisielewska,^{81a} V. Kitali,⁴⁴ O. Kivernyk,⁵ E. Kladiava,^{28b,a} T. Klapdor-Kleingrothaus,⁵⁰ M. H. Klein,¹⁰³ M. Klein,⁸⁸
U. Klein,⁸⁸ K. Kleinknecht,⁹⁷ P. Klimek,¹¹⁹ A. Klimentov,²⁹ T. Klingl,²⁴ T. Klioutchnikova,³⁵ F. F. Klitzner,¹¹² P. Kluit,¹¹⁸
S. Kluth,¹¹³ E. Kneringer,⁷⁴ E. B. F. G. Knoops,⁹⁹ A. Knue,⁵⁰ A. Kobayashi,¹⁶⁰ D. Kobayashi,⁸⁵ T. Kobayashi,¹⁶⁰
M. Kobel,⁴⁶ M. Kocian,¹⁵⁰ P. Kodys,¹⁴⁰ P. T. Koenig,²⁴ T. Koffas,³³ E. Koffeman,¹¹⁸ N. M. Köhler,¹¹³ T. Koi,¹⁵⁰ M. Kolb,^{59b}
I. Koletsou,⁵ T. Kondo,⁷⁹ N. Kondrashova,^{58c} K. Köneke,⁵⁰ A. C. König,¹¹⁷ T. Kono,⁷⁹ R. Konoplich,^{122,hh}
V. Konstantinides,⁹² N. Konstantinidis,⁹² B. Konya,⁹⁴ R. Kopeliansky,⁶³ S. Koperny,^{81a} K. Korcyl,⁸² K. Kordas,¹⁵⁹
G. Koren,¹⁵⁸ A. Korn,⁹² I. Korolkov,¹⁴ E. V. Korolkova,¹⁴⁶ N. Korotkova,¹¹¹ O. Kortner,¹¹³ S. Kortner,¹¹³ T. Kosek,¹⁴⁰
V. V. Kostyukhin,²⁴ A. Kotwal,⁴⁷ A. Koulouris,¹⁰ A. Kourkouveli-Charalampidi,^{68a,68b} C. Kourkouvelis,⁹ E. Kourlitis,¹⁴⁶
V. Kouskoura,²⁹ A. B. Kowalewska,⁸² R. Kowalewski,¹⁷³ T. Z. Kowalski,^{81a} C. Kozakai,¹⁶⁰ W. Kozanecki,¹⁴²
A. S. Kozhin,¹²¹ V. A. Kramarenko,¹¹¹ G. Kramberger,⁸⁹ D. Krasnopevtsev,^{58a} M. W. Krasny,¹³³ A. Krasznahorkay,³⁵
D. Krauss,¹¹³ J. A. Kremer,^{81a} J. Kretschmar,⁸⁸ P. Krieger,¹⁶⁴ K. Krizka,¹⁸ K. Kroeninger,⁴⁵ H. Kroha,¹¹³ J. Kroll,¹³⁸
J. Kroll,¹³⁴ J. Krstic,¹⁶ U. Kruchonak,⁷⁷ H. Krüger,²⁴ N. Krumnack,⁷⁶ M. C. Kruse,⁴⁷ T. Kubota,¹⁰² S. Kuday,^{4b}
J. T. Kuechler,¹⁷⁹ S. Kuehn,³⁵ A. Kugel,^{59a} T. Kuhl,⁴⁴ V. Kukhtin,⁷⁷ R. Kukla,⁹⁹ Y. Kulchitsky,^{105,ii} S. Kuleshov,^{144b}
Y. P. Kulinich,¹⁷⁰ M. Kuna,⁵⁶ T. Kunigo,⁸³ A. Kupco,¹³⁸ T. Kupfer,⁴⁵ O. Kuprash,¹⁵⁸ H. Kurashige,⁸⁰ L. L. Kurchaninov,^{165a}
Y. A. Kurochkin,¹⁰⁵ A. Kurova,¹¹⁰ M. G. Kurth,^{15d} E. S. Kuwertz,³⁵ M. Kuze,¹⁶² J. Kvita,¹²⁷ T. Kwan,¹⁰¹ A. La Rosa,¹¹³
J. L. La Rosa Navarro,^{78d} L. La Rotonda,^{40b,40a} F. La Ruffa,^{40b,40a} C. Lacasta,¹⁷¹ F. Lacava,^{70a,70b} J. Lacey,⁴⁴ D. P. J. Lack,⁹⁸
H. Lacker,¹⁹ D. Lacour,¹³³ E. Ladygin,⁷⁷ R. Lafaye,⁵ B. Laforge,¹³³ T. Lagouri,^{32c} S. Lai,⁵¹ S. Lammers,⁶³ W. Lampl,⁷
E. Lançon,²⁹ U. Landgraf,⁵⁰ M. P. J. Landon,⁹⁰ M. C. Lanfermann,⁵² V. S. Lang,⁴⁴ J. C. Lange,⁵¹ R. J. Langenberg,³⁵
A. J. Lankford,¹⁶⁸ F. Lanni,²⁹ K. Lantzsch,²⁴ A. Lanza,^{68a} A. Lapertosa,^{53b,53a} S. Laplace,¹³³ J. F. Laporte,¹⁴² T. Lari,^{66a}
F. Lasagni Manghi,^{23b,23a} M. Lassnig,³⁵ T. S. Lau,^{61a} A. Laudrain,¹²⁹ M. Lavorgna,^{67a,67b} M. Lazzaroni,^{66a,66b} B. Le,¹⁰²
O. Le Dortz,¹³³ E. Le Guirriec,⁹⁹ E. P. Le Quilleuc,¹⁴² M. LeBlanc,⁷ T. LeCompte,⁶ F. Ledroit-Guillon,⁵⁶ C. A. Lee,²⁹
G. R. Lee,^{144a} L. Lee,⁵⁷ S. C. Lee,¹⁵⁵ B. Lefebvre,¹⁰¹ M. Lefebvre,¹⁷³ F. Legger,¹¹² C. Leggett,¹⁸ K. Lehmann,¹⁴⁹
N. Lehmann,¹⁷⁹ G. Lehmann Miotto,³⁵ W. A. Leight,⁴⁴ A. Leisos,^{159,jj} M. A. L. Leite,^{78d} R. Leitner,¹⁴⁰ D. Lellouch,¹⁷⁷
K. J. C. Leney,⁹² T. Lenz,²⁴ B. Lenzi,³⁵ R. Leone,⁷ S. Leone,^{69a} C. Leonidopoulos,⁴⁸ G. Lerner,¹⁵³ C. Leroy,¹⁰⁷ R. Les,¹⁶⁴
A. A. J. Lesage,¹⁴² C. G. Lester,³¹ M. Levchenko,¹³⁵ J. Levêque,⁵ D. Levin,¹⁰³ L. J. Levinson,¹⁷⁷ D. Lewis,⁹⁰ B. Li,^{15b}

- B. Li,¹⁰³ C-Q. Li,^{58a,kk} H. Li,^{58a} H. Li,^{58b} L. Li,^{58c} M. Li,^{15a} Q. Li,^{15d} Q. Y. Li,^{58a} S. Li,^{58d,58c} X. Li,^{58c} Y. Li,¹⁴⁸ Z. Liang,^{15a}
 B. Liberti,^{71a} A. Liblong,¹⁶⁴ K. Lie,^{61c} S. Liem,¹¹⁸ A. Limosani,¹⁵⁴ C. Y. Lin,³¹ K. Lin,¹⁰⁴ T. H. Lin,⁹⁷ R. A. Linck,⁶³
 J. H. Lindon,²¹ B. E. Lindquist,¹⁵² A. L. Lioni,⁵² E. Lipeles,¹³⁴ A. Lipniacka,¹⁷ M. Lisovyi,^{59b} T. M. Liss,^{170,II} A. Lister,¹⁷²
 A. M. Litke,¹⁴³ J. D. Little,⁸ B. Liu,⁷⁶ B. L. Liu,⁶ H. B. Liu,²⁹ H. Liu,¹⁰³ J. B. Liu,^{58a} J. K. K. Liu,¹³² K. Liu,¹³³ M. Liu,^{58a}
 P. Liu,¹⁸ Y. Liu,^{15a} Y. L. Liu,^{58a} Y. W. Liu,^{58a} M. Livan,^{68a,68b} A. Lleres,⁵⁶ J. Llorente Merino,^{15a} S. L. Lloyd,⁹⁰ C. Y. Lo,^{61b}
 F. Lo Sterzo,⁴¹ E. M. Lobodzinska,⁴⁴ P. Loch,⁷ T. Lohse,¹⁹ K. Lohwasser,¹⁴⁶ M. Lokajicek,¹³⁸ J. D. Long,¹⁷⁰ R. E. Long,⁸⁷
 L. Longo,^{65a,65b} K. A. Looper,¹²³ J. A. Lopez,^{144b} I. Lopez Paz,⁹⁸ A. Lopez Solis,¹⁴⁶ J. Lorenz,¹¹² N. Lorenzo Martinez,⁵
 M. Losada,²² P. J. Lösel,¹¹² A. Lösle,⁵⁰ X. Lou,⁴⁴ X. Lou,^{15a} A. Lounis,¹²⁹ J. Love,⁶ P. A. Love,⁸⁷ J. J. Lozano Bahilo,¹⁷¹
 H. Lu,^{61a} M. Lu,^{58a} Y. J. Lu,⁶² H. J. Lubatti,¹⁴⁵ C. Luci,^{70a,70b} A. Lucotte,⁵⁶ C. Luedtke,⁵⁰ F. Luehring,⁶³ I. Luise,¹³³
 L. Luminari,^{70a} B. Lund-Jensen,¹⁵¹ M. S. Lutz,¹⁰⁰ P. M. Luzzi,¹³³ D. Lynn,²⁹ R. Lysak,¹³⁸ E. Lytken,⁹⁴ F. Lyu,^{15a}
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 K. Maekawa,¹⁶⁰ S. Maeland,¹⁷ T. Maeno,²⁹ M. Maerker,⁴⁶ A. S. Maevskiy,¹¹¹ V. Magerl,⁵⁰ D. J. Mahon,³⁸
 C. Maidantchik,^{78b} T. Maier,¹¹² A. Maio,^{137a,137b,137d} O. Majersky,^{28a} S. Majewski,¹²⁸ Y. Makida,⁷⁹ N. Makovec,¹²⁹
 B. Malaescu,¹³³ Pa. Malecki,⁸² V. P. Maleev,¹³⁵ F. Malek,⁵⁶ U. Mallik,⁷⁵ D. Malon,⁶ C. Malone,³¹ S. Maltezos,¹⁰
 S. Malyukov,³⁵ J. Mamuzic,¹⁷¹ G. Mancini,⁴⁹ I. Mandić,⁸⁹ J. Maneira,^{137a} L. Manhaes de Andrade Filho,^{78a}
 J. Manjarres Ramos,⁴⁶ K. H. Mankinen,⁹⁴ A. Mann,¹¹² A. Manousos,⁷⁴ B. Mansoulie,¹⁴² S. Manzoni,^{66a,66b} A. Marantis,¹⁵⁹
 G. Marceca,³⁰ L. March,⁵² L. Marchese,¹³² G. Marchiori,¹³³ M. Marcisovsky,¹³⁸ C. Marcon,⁹⁴ C. A. Marin Tobon,³⁵
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 T. A. Martin,¹⁷⁵ V. J. Martin,⁴⁸ B. Martin dit Latour,¹⁷ M. Martinez,^{14,y} V. I. Martinez Outschoorn,¹⁰⁰ S. Martin-Haugh,¹⁴¹
 V. S. Martoiu,^{27b} A. C. Martyniuk,⁹² A. Marzin,³⁵ L. Masetti,⁹⁷ T. Mashimo,¹⁶⁰ R. Mashinistov,¹⁰⁸ J. Masik,⁹⁸
 A. L. Maslennikov,^{120b,120a} L. H. Mason,¹⁰² L. Massa,^{71a,71b} P. Massarotti,^{67a,67b} P. Mastrandrea,¹⁵² A. Mastroberardino,^{40b,40a}
 T. Masubuchi,¹⁶⁰ P. Mättig,²⁴ J. Maurer,^{27b} B. Maček,⁸⁹ S. J. Maxfield,⁸⁸ D. A. Maximov,^{120b,120a} R. Mazini,¹⁵⁵ I. Maznas,¹⁵⁹
 S. M. Mazza,¹⁴³ S. P. Mc Kee,¹⁰³ A. McCarn,⁴¹ T. G. McCarthy,¹¹³ L. I. McClymont,⁹² W. P. McCormack,¹⁸
 E. F. McDonald,¹⁰² J. A. Mcfayden,³⁵ G. Mchedlidze,⁵¹ M. A. McKay,⁴¹ K. D. McLean,¹⁷³ S. J. McMahon,¹⁴¹
 P. C. McNamara,¹⁰² C. J. McNicol,¹⁷⁵ R. A. McPherson,^{173,n} J. E. Mdhuli,^{32c} Z. A. Meadows,¹⁰⁰ S. Meehan,¹⁴⁵
 T. M. Megy,⁵⁰ S. Mehlhase,¹¹² A. Mehta,⁸⁸ T. Meideck,⁵⁶ B. Meirose,⁴² D. Melini,^{171,mm} B. R. Mellado Garcia,^{32c}
 J. D. Mellenthin,⁵¹ M. Melo,^{28a} F. Meloni,⁴⁴ A. Melzer,²⁴ S. B. Menary,⁹⁸ E. D. Mendes Gouveia,^{137a} L. Meng,⁸⁸
 X. T. Meng,¹⁰³ S. Menke,¹¹³ E. Meoni,^{40b,40a} S. Mergelmeyer,¹⁹ S. A. M. Merkt,¹³⁶ C. Merlassino,²⁰ P. Mermod,⁵²
 L. Merola,^{67a,67b} C. Meroni,^{66a} F. S. Merritt,³⁶ A. Messina,^{70a,70b} J. Metcalfe,⁶ A. S. Mete,¹⁶⁸ C. Meyer,⁶³ J. Meyer,¹⁵⁷
 J-P. Meyer,¹⁴² H. Meyer Zu Theenhausen,^{59a} F. Miano,¹⁵³ R. P. Middleton,¹⁴¹ L. Mijović,⁴⁸ G. Mikenberg,¹⁷⁷
 M. Mikestikova,¹³⁸ M. Mikuž,⁸⁹ M. Milesi,¹⁰² A. Milic,¹⁶⁴ D. A. Millar,⁹⁰ D. W. Miller,³⁶ A. Milov,¹⁷⁷ D. A. Milstead,^{43a,43b}
 R. A. Mina,^{150,gg} A. A. Minaenko,¹²¹ M. Miñano Moya,¹⁷¹ I. A. Minashvili,^{156b} A. I. Mincer,¹²² B. Mindur,^{81a} M. Mineev,⁷⁷
 Y. Minegishi,¹⁶⁰ Y. Ming,¹⁷⁸ L. M. Mir,¹⁴ A. Mirto,^{65a,65b} K. P. Mistry,¹³⁴ T. Mitani,¹⁷⁶ J. Mitrevski,¹¹² V. A. Mitsou,¹⁷¹
 M. Mittal,^{58c} A. Miucci,²⁰ P. S. Miyagawa,¹⁴⁶ A. Mizukami,⁷⁹ J. U. Mjörnmark,⁹⁴ T. Mkrtchyan,¹⁸¹ M. Mlynarikova,¹⁴⁰
 T. Moa,^{43a,43b} K. Mochizuki,¹⁰⁷ P. Mogg,⁵⁰ S. Mohapatra,³⁸ S. Molander,^{43a,43b} R. Moles-Valls,²⁴ M. C. Mondragon,¹⁰⁴
 K. Mönig,⁴⁴ J. Monk,³⁹ E. Monnier,⁹⁹ A. Montalbano,¹⁴⁹ J. Montejo Berlingen,³⁵ F. Monticelli,⁸⁶ S. Monzani,^{66a}
 N. Morange,¹²⁹ D. Moreno,²² M. Moreno Llacer,³⁵ P. Morettini,^{53b} M. Morgenstern,¹¹⁸ S. Morgenstern,⁴⁶ D. Mori,¹⁴⁹
 M. Morii,⁵⁷ M. Morinaga,¹⁷⁶ V. Morisbak,¹³¹ A. K. Morley,³⁵ G. Mornacchi,³⁵ A. P. Morris,⁹² J. D. Morris,⁹⁰ L. Morvaj,¹⁵²
 P. Moschovakos,¹⁰ M. Mosidze,^{156b} H. J. Moss,¹⁴⁶ J. Moss,^{150,nn} K. Motohashi,¹⁶² R. Mount,¹⁵⁰ E. Mountricha,³⁵
 E. J. W. Moyse,¹⁰⁰ S. Muanza,⁹⁹ F. Mueller,¹¹³ J. Mueller,¹³⁶ R. S. P. Mueller,¹¹² D. Muenstermann,⁸⁷ G. A. Mullier,⁹⁴
 F. J. Munoz Sanchez,⁹⁸ P. Murin,^{28b} W. J. Murray,^{175,141} A. Murrone,^{66a,66b} M. Muškinja,⁸⁹ C. Mwewa,^{32a}
 A. G. Myagkov,^{121,oo} J. Myers,¹²⁸ M. Myska,¹³⁹ B. P. Nachman,¹⁸ O. Nackenhorst,⁴⁵ K. Nagai,¹³² K. Nagano,⁷⁹
 Y. Nagasaka,⁶⁰ M. Nagel,⁵⁰ E. Nagy,⁹⁹ A. M. Nairz,³⁵ Y. Nakahama,¹¹⁵ K. Nakamura,⁷⁹ T. Nakamura,¹⁶⁰ I. Nakano,¹²⁴
 H. Nanjo,¹³⁰ F. Napolitano,^{59a} R. F. Naranjo Garcia,⁴⁴ R. Narayan,¹¹ D. I. Narrias Villar,^{59a} I. Naryshkin,¹³⁵ T. Naumann,⁴⁴
 G. Navarro,²² R. Nayyar,⁷ H. A. Neal,^{103,a} P. Y. Nechaeva,¹⁰⁸ T. J. Neep,¹⁴² A. Negri,^{68a,68b} M. Negrini,^{23b} S. Nektarijevic,¹¹⁷
 C. Nellist,⁵¹ M. E. Nelson,¹³² S. Nemecek,¹³⁸ P. Nemethy,¹²² M. Nessi,^{35,pp} M. S. Neubauer,¹⁷⁰ M. Neumann,¹⁷⁹
 P. R. Newman,²¹ T. Y. Ng,^{61c} Y. S. Ng,¹⁹ Y. W. Y. Ng,¹⁶⁸ H. D. N. Nguyen,⁹⁹ T. Nguyen Manh,¹⁰⁷ E. Nibigira,³⁷
 R. B. Nickerson,¹³² R. Nicolaidou,¹⁴² D. S. Nielsen,³⁹ J. Nielsen,¹⁴³ N. Nikiforou,¹¹ V. Nikolaenko,^{121,oo} I. Nikolic-Audit,¹³³

- K. Nikolopoulos,²¹ P. Nilsson,²⁹ H. R. Nindhito,⁵² Y. Ninomiya,⁷⁹ A. Nisati,^{70a} N. Nishu,^{58c} R. Nisius,¹¹³ I. Nitsche,⁴⁵ T. Nitta,¹⁷⁶ T. Nobe,¹⁶⁰ Y. Noguchi,⁸³ M. Nomachi,¹³⁰ I. Nomidis,¹³³ M. A. Nomura,²⁹ T. Nooney,⁹⁰ M. Nordberg,³⁵ N. Norjoharuddeen,¹³² T. Novak,⁸⁹ O. Novgorodova,⁴⁶ R. Novotny,¹³⁹ L. Nozka,¹²⁷ K. Ntekas,¹⁶⁸ E. Nurse,⁹² F. Nuti,¹⁰² F. G. Oakham,^{33,f} H. Oberlack,¹¹³ J. Ocariz,¹³³ A. Ochi,⁸⁰ I. Ochoa,³⁸ J. P. Ochoa-Ricoux,^{144a} K. O'Connor,²⁶ S. Oda,⁸⁵ S. Odaka,⁷⁹ S. Oerdek,⁵¹ A. Oh,⁹⁸ S. H. Oh,⁴⁷ C. C. Ohm,¹⁵¹ H. Oide,^{53b,53a} M. L. Ojeda,¹⁶⁴ H. Okawa,¹⁶⁶ Y. Okazaki,⁸³ Y. Okumura,¹⁶⁰ T. Okuyama,⁷⁹ A. Olariu,^{27b} L. F. Oleiro Seabra,^{137a} S. A. Olivares Pino,^{144a} D. Oliveira Damazio,²⁹ J. L. Oliver,¹ M. J. R. Olsson,³⁶ A. Olszewski,⁸² J. Olszowska,⁸² D. C. O'Neil,¹⁴⁹ A. Onofre,^{137a,137e} K. Onogi,¹¹⁵ P. U. E. Onyisi,¹¹ H. Oppen,¹³¹ M. J. Oreglia,³⁶ G. E. Orellana,⁸⁶ Y. Oren,¹⁵⁸ D. Orestano,^{72a,72b} E. C. Orgill,⁹⁸ N. Orlando,^{61b} A. A. O'Rourke,⁴⁴ R. S. Orr,¹⁶⁴ B. Osculati,^{53b,53a,a} V. O'Shea,⁵⁵ R. Ospanov,^{58a} G. Otero y Garzon,³⁰ H. Otono,⁸⁵ M. Ouchrif,^{34d} F. Ould-Saada,¹³¹ A. Ouraou,¹⁴² Q. Ouyang,^{15a} M. Owen,⁵⁵ R. E. Owen,²¹ V. E. Ozcan,^{12c} N. Ozturk,⁸ J. Pacalt,¹²⁷ H. A. Pacey,³¹ K. Pachal,¹⁴⁹ A. Pacheco Pages,¹⁴ L. Pacheco Rodriguez,¹⁴² C. Padilla Aranda,¹⁴ S. Pagan Griso,¹⁸ M. Paganini,¹⁸⁰ G. Palacino,⁶³ S. Palazzo,⁴⁸ S. Palestini,³⁵ M. Palka,^{81b} D. Pallin,³⁷ I. Panagoulas,¹⁰ C. E. Pandini,³⁵ J. G. Panduro Vazquez,⁹¹ P. Pani,³⁵ G. Panizzo,^{64a,64c} L. Paolozzi,⁵² T. D. Papadopoulou,¹⁰ K. Papageorgiou,^{9,u} A. Paramonov,⁶ D. Paredes Hernandez,^{61b} S. R. Paredes Saenz,¹³² B. Parida,¹⁶³ T. H. Park,³³ A. J. Parker,⁸⁷ K. A. Parker,⁴⁴ M. A. Parker,³¹ F. Parodi,^{53b,53a} J. A. Parsons,³⁸ U. Parzefall,⁵⁰ V. R. Pascuzzi,¹⁶⁴ J. M. P. Pasner,¹⁴³ E. Pasqualucci,^{70a} S. Passaggio,^{53b} F. Pastore,⁹¹ P. Pasuwan,^{43a,43b} S. Pataaraia,⁹⁷ J. R. Pater,⁹⁸ A. Pathak,^{178,g} T. Pauly,³⁵ B. Pearson,¹¹³ M. Pedersen,¹³¹ L. Pedraza Diaz,¹¹⁷ R. Pedro,^{137a,137b} S. V. Peleganchuk,^{120b,120a} O. Penc,¹³⁸ C. Peng,^{15d} H. Peng,^{58a} B. S. Peralva,^{78a} M. M. Perego,¹²⁹ A. P. Pereira Peixoto,^{137a} D. V. Perepelitsa,²⁹ F. Peri,¹⁹ L. Perini,^{66a,66b} H. Pernegger,³⁵ S. Perrella,^{67a,67b} V. D. Peshekhonov,^{77,a} K. Peters,⁴⁴ R. F. Y. Peters,⁹⁸ B. A. Petersen,³⁵ T. C. Petersen,³⁹ E. Petit,⁵⁶ A. Petridis,¹ C. Petridou,¹⁵⁹ P. Petroff,¹²⁹ M. Petrov,¹³² F. Petrucci,^{72a,72b} M. Pettee,¹⁸⁰ N. E. Pettersson,¹⁰⁰ A. Peyaud,¹⁴² R. Pezoa,^{144b} T. Pham,¹⁰² F. H. Phillips,¹⁰⁴ P. W. Phillips,¹⁴¹ M. W. Phipps,¹⁷⁰ G. Piacquadio,¹⁵² E. Pianori,¹⁸ A. Picazio,¹⁰⁰ R. H. Pickles,⁹⁸ R. Piegaia,³⁰ J. E. Pilcher,³⁶ A. D. Pilkington,⁹⁸ M. Pinamonti,^{71a,71b} J. L. Pinfold,³ M. Pitt,¹⁷⁷ L. Pizzimento,^{71a,71b} M.-A. Pleier,²⁹ V. Pleskot,¹⁴⁰ E. Plotnikova,⁷⁷ D. Pluth,⁷⁶ P. Podberezko,^{120b,120a} R. Poettgen,⁹⁴ R. Poggi,⁵² L. Poggioli,¹²⁹ I. Pogrebnyak,¹⁰⁴ D. Pohl,²⁴ I. Pokharel,⁵¹ G. Polesello,^{68a} A. Poley,¹⁸ A. Policicchio,^{70a,70b} R. Polifka,³⁵ A. Polini,^{23b} C. S. Pollard,⁴⁴ V. Polychronakos,²⁹ D. Ponomarenko,¹¹⁰ L. Pontecorvo,³⁵ G. A. Popeneciu,^{27d} D. M. Portillo Quintero,¹³³ S. Pospisil,¹³⁹ K. Potamianos,⁴⁴ I. N. Potrap,⁷⁷ C. J. Potter,³¹ H. Potti,¹¹ T. Poulsen,⁹⁴ J. Poveda,³⁵ T. D. Powell,¹⁴⁶ M. E. Pozo Astigarraga,³⁵ P. Pralavorio,⁹⁹ S. Prell,⁷⁶ D. Price,⁹⁸ M. Primavera,^{65a} S. Prince,¹⁰¹ M. L. Proffitt,¹⁴⁵ N. Proklova,¹¹⁰ K. Prokofiev,^{61c} F. Prokoshin,^{144b} S. Protopopescu,²⁹ J. Proudfoot,⁶ M. Przybycien,^{81a} A. Puri,¹⁷⁰ P. Puzo,¹²⁹ J. Qian,¹⁰³ Y. Qin,⁹⁸ A. Quadt,⁵¹ M. Queitsch-Maitland,⁴⁴ A. Qureshi,¹ P. Rados,¹⁰² F. Ragusa,^{66a,66b} G. Rahal,⁹⁵ J. A. Raine,⁵² S. Rajagopalan,²⁹ A. Ramirez Morales,⁹⁰ K. Ran,^{15a} T. Rashid,¹²⁹ S. Raspopov,⁵ M. G. Ratti,^{66a,66b} D. M. Rauch,⁴⁴ F. Rauscher,¹¹² S. Rave,⁹⁷ B. Ravina,¹⁴⁶ I. Ravinovich,¹⁷⁷ J. H. Rawling,⁹⁸ M. Raymond,³⁵ A. L. Read,¹³¹ N. P. Readioff,⁵⁶ M. Reale,^{65a,65b} D. M. Rebuzzi,^{68a,68b} A. Redelbach,¹⁷⁴ G. Redlinger,²⁹ R. Reece,¹⁴³ R. G. Reed,^{32c} K. Reeves,⁴² L. Rehnisch,¹⁹ J. Reichert,¹³⁴ D. Reikher,¹⁵⁸ A. Reiss,⁹⁷ A. Rej,¹⁴⁸ C. Rembser,³⁵ H. Ren,^{15d} M. Rescigno,^{70a} S. Resconi,^{66a} E. D. Resseguie,¹³⁴ S. Rettie,¹⁷² E. Reynolds,²¹ O. L. Rezanova,^{120b,120a} P. Reznicek,¹⁴⁰ E. Ricci,^{73a,73b} R. Richter,¹¹³ S. Richter,⁴⁴ E. Richter-Was,^{81b} O. Ricken,²⁴ M. Ridel,¹³³ P. Rieck,¹¹³ C. J. Riegel,¹⁷⁹ O. Rifki,⁴⁴ M. Rijssenbeek,¹⁵² A. Rimoldi,^{68a,68b} M. Rimoldi,²⁰ L. Rinaldi,^{23b} G. Ripellino,¹⁵¹ B. Ristić,⁸⁷ E. Ritsch,³⁵ I. Riu,¹⁴ J. C. Rivera Vergara,^{144a} F. Rizatdinova,¹²⁶ E. Rizvi,⁹⁰ C. Rizzi,¹⁴ R. T. Roberts,⁹⁸ S. H. Robertson,^{101,n} D. Robinson,³¹ J. E. M. Robinson,⁴⁴ A. Robson,⁵⁵ E. Rocco,⁹⁷ C. Roda,^{69a,69b} Y. Rodina,⁹⁹ S. Rodriguez Bosca,¹⁷¹ A. Rodriguez Perez,¹⁴ D. Rodriguez Rodriguez,¹⁷¹ A. M. Rodríguez Vera,^{165b} S. Roe,³⁵ C. S. Rogan,⁵⁷ O. Røhne,¹³¹ R. Röhrig,¹¹³ C. P. A. Roland,⁶³ J. Roloff,⁵⁷ A. Romaniouk,¹¹⁰ M. Romano,^{23b,23a} N. Rompotis,⁸⁸ M. Ronzani,¹²² L. Roos,¹³³ S. Rosati,^{70a} K. Rosbach,⁵⁰ N.-A. Rosien,⁵¹ B. J. Rosser,¹³⁴ E. Rossi,⁴⁴ E. Rossi,^{72a,72b} E. Rossi,^{67a,67b} L. P. Rossi,^{53b} L. Rossini,^{66a,66b} J. H. N. Rosten,³¹ R. Rosten,¹⁴ M. Rotaru,^{27b} J. Rothberg,¹⁴⁵ D. Rousseau,¹²⁹ D. Roy,^{32c} A. Rozanov,⁹⁹ Y. Rozen,¹⁵⁷ X. Ruan,^{32c} F. Rubbo,¹⁵⁰ F. Rühr,⁵⁰ A. Ruiz-Martinez,¹⁷¹ Z. Rurikova,⁵⁰ N. A. Rusakovich,⁷⁷ H. L. Russell,¹⁰¹ J. P. Rutherford,⁷ E. M. Rüttinger,^{44,qq} Y. F. Ryabov,¹³⁵ M. Rybar,³⁸ G. Rybkin,¹²⁹ S. Ryu,⁶ A. Ryzhov,¹²¹ G. F. Rzehorz,⁵¹ P. Sabatini,⁵¹ G. Sabato,¹¹⁸ S. Sacerdoti,¹²⁹ H. F.-W. Sadrozinski,¹⁴³ R. Sadykov,⁷⁷ F. Safai Tehrani,^{70a} P. Saha,¹¹⁹ M. Sahinsoy,^{59a} A. Sahu,¹⁷⁹ M. Saimpert,⁴⁴ M. Saito,¹⁶⁰ T. Saito,¹⁶⁰ H. Sakamoto,¹⁶⁰ A. Sakharov,^{122,hb} D. Salamani,⁵² G. Salamanna,^{72a,72b} J. E. Salazar Loyola,^{144b} P. H. Sales De Bruin,¹⁶⁹ D. Salihagic,¹¹³ A. Salnikov,¹⁵⁰ J. Salt,¹⁷¹ D. Salvatore,^{40b,40a} F. Salvatore,¹⁵³ A. Salvucci,^{61a,61b,61c} A. Salzburger,³⁵ J. Samarati,³⁵ D. Sammel,⁵⁰ D. Sampsonidis,¹⁵⁹

- D. Sampsonidou,¹⁵⁹ J. Sánchez,¹⁷¹ A. Sanchez Pineda,^{64a,64c} H. Sandaker,¹³¹ C. O. Sander,⁴⁴ M. Sandhoff,¹⁷⁹ C. Sandoval,²²
D. P. C. Sankey,¹⁴¹ M. Sannino,^{53b,53a} Y. Sano,¹¹⁵ A. Sansoni,⁴⁹ C. Santoni,³⁷ H. Santos,^{137a} I. Santoyo Castillo,¹⁵³
A. Santra,¹⁷¹ A. Sapronov,⁷⁷ J. G. Saraiva,^{137a,137d} O. Sasaki,⁷⁹ K. Sato,¹⁶⁶ E. Sauvan,⁵ P. Savard,^{164,f} N. Savic,¹¹³
R. Sawada,¹⁶⁰ C. Sawyer,¹⁴¹ L. Sawyer,^{93,w} C. Sbarra,^{23b} A. Sbrizzi,^{23a} T. Scanlon,⁹² J. Schaarschmidt,¹⁴⁵ P. Schacht,¹¹³
B. M. Schachtner,¹¹² D. Schaefer,³⁶ L. Schaefer,¹³⁴ J. Schaeffer,⁹⁷ S. Schaepe,³⁵ U. Schäfer,⁹⁷ A. C. Schaffer,¹²⁹
D. Schaile,¹¹² R. D. Schamberger,¹⁵² N. Scharmberg,⁹⁸ V. A. Schegelsky,¹³⁵ D. Scheirich,¹⁴⁰ F. Schenck,¹⁹ M. Schernau,¹⁶⁸
C. Schiavi,^{53b,53a} S. Schier,¹⁴³ L. K. Schildgen,²⁴ Z. M. Schillaci,²⁶ E. J. Schioppa,³⁵ M. Schioppa,^{40b,40a} K. E. Schleicher,⁵⁰
S. Schlenker,³⁵ K. R. Schmidt-Sommerfeld,¹¹³ K. Schmieden,³⁵ C. Schmitt,⁹⁷ S. Schmitt,⁴⁴ S. Schmitz,⁹⁷
J. C. Schmoeckel,⁴⁴ U. Schnoor,⁵⁰ L. Schoeffel,¹⁴² A. Schoening,^{59b} E. Schopf,¹³² M. Schott,⁹⁷ J. F. P. Schouwenberg,¹¹⁷
J. Schovancova,³⁵ S. Schramm,⁵² A. Schulte,⁹⁷ H-C. Schultz-Coulon,^{59a} M. Schumacher,⁵⁰ B. A. Schumm,¹⁴³
Ph. Schune,¹⁴² A. Schwartzman,¹⁵⁰ T. A. Schwarz,¹⁰³ Ph. Schwemling,¹⁴² R. Schwienhorst,¹⁰⁴ A. Sciandra,²⁴ G. Sciolla,²⁶
M. Scornajenghi,^{40b,40a} F. Scuri,^{69a} F. Scutti,¹⁰² L. M. Scyboz,¹¹³ C. D. Sebastiani,^{70a,70b} P. Seema,¹⁹ S. C. Seidel,¹¹⁶
A. Seiden,¹⁴³ T. Seiss,³⁶ J. M. Seixas,^{78b} G. Sekhniaidze,^{67a} K. Sekhon,¹⁰³ S. J. Sekula,⁴¹ N. Semprini-Cesari,^{23b,23a} S. Sen,⁴⁷
S. Senkin,³⁷ C. Serfon,¹³¹ L. Serin,¹²⁹ L. Serkin,^{64a,64b} M. Sessa,^{58a} H. Severini,¹²⁵ F. Sforza,¹⁶⁷ A. Sfyrila,⁵² E. Shabalina,⁵¹
J. D. Shahinian,¹⁴³ N. W. Shaikh,^{43a,43b} D. Shaked Renous,¹⁷⁷ L. Y. Shan,^{15a} R. Shang,¹⁷⁰ J. T. Shank,²⁵ M. Shapiro,¹⁸
A. S. Sharma,¹ A. Sharma,¹³² P. B. Shatalov,¹⁰⁹ K. Shaw,¹⁵³ S. M. Shaw,⁹⁸ A. Shcherbakova,¹³⁵ Y. Shen,¹²⁵ N. Sherafati,³³
A. D. Sherman,²⁵ P. Sherwood,⁹² L. Shi,^{155,rr} S. Shimizu,⁷⁹ C. O. Shimmin,¹⁸⁰ Y. Shimogama,¹⁷⁶ M. Shimojima,¹¹⁴
I. P. J. Shipsey,¹³² S. Shirabe,⁸⁵ M. Shiyakova,⁷⁷ J. Shlomi,¹⁷⁷ A. Shmeleva,¹⁰⁸ D. Shoaleh Saadi,¹⁰⁷ M. J. Shochet,³⁶
S. Shojaii,¹⁰² D. R. Shope,¹²⁵ S. Shrestha,¹²³ E. Shulga,¹¹⁰ P. Sicho,¹³⁸ A. M. Sickles,¹⁷⁰ P. E. Sidebo,¹⁵¹
E. Sideras Haddad,^{32c} O. Sidiropoulou,³⁵ A. Sidoti,^{23b,23a} F. Siegert,⁴⁶ Dj. Sijacki,¹⁶ J. Silva,^{137a} M. Silva Jr.,¹⁷⁸
M. V. Silva Oliveira,^{78a} S. B. Silverstein,^{43a} S. Simion,¹²⁹ E. Simioni,⁹⁷ M. Simon,⁹⁷ R. Simoniello,⁹⁷ P. Sinervo,¹⁶⁴
N. B. Sinev,¹²⁸ M. Sioli,^{23b,23a} I. Siral,¹⁰³ S. Yu. Sivoklov,¹¹¹ J. Sjölin,^{43a,43b} P. Skubic,¹²⁵ M. Slater,²¹ T. Slavicek,¹³⁹
M. Slawinska,⁸² K. Sliwa,¹⁶⁷ R. Slovak,¹⁴⁰ V. Smakhtin,¹⁷⁷ B. H. Smart,⁵ J. Smiesko,^{28a} N. Smirnov,¹¹⁰ S. Yu. Smirnov,¹¹⁰
Y. Smirnov,¹¹⁰ L. N. Smirnova,¹¹¹ O. Smirnova,⁹⁴ J. W. Smith,⁵¹ M. Smizanska,⁸⁷ K. Smolek,¹³⁹ A. Smykiewicz,⁸²
A. A. Snesarev,¹⁰⁸ I. M. Snyder,¹²⁸ S. Snyder,²⁹ R. Sobie,^{173,n} A. M. Soffa,¹⁶⁸ A. Soffer,¹⁵⁸ A. Søggaard,⁴⁸ F. Sohns,⁵¹
G. Sokhrannyi,⁸⁹ C. A. Solans Sanchez,³⁵ M. Solar,¹³⁹ E. Yu. Soldatov,¹¹⁰ U. Soldevila,¹⁷¹ A. A. Solodkov,¹²¹
A. Soloshenko,⁷⁷ O. V. Solovyanov,¹²¹ V. Solovyev,¹³⁵ P. Sommer,¹⁴⁶ H. Son,¹⁶⁷ W. Song,¹⁴¹ W. Y. Song,^{165b} A. Sopczak,¹³⁹
F. Sopkova,^{28b} C. L. Sotiropoulou,^{69a,69b} S. Sottocornola,^{68a,68b} R. Soualah,^{64a,64c,ss} A. M. Soukharev,^{120b,120a} D. South,⁴⁴
S. Spagnolo,^{65a,65b} M. Spalla,¹¹³ M. Spangenberg,¹⁷⁵ F. Spanò,⁹¹ D. Sperlich,¹⁹ T. M. Spieker,^{59a} R. Spighi,^{23b} G. Spigo,³⁵
L. A. Spiller,¹⁰² D. P. Spiteri,⁵⁵ M. Spousta,¹⁴⁰ A. Stabile,^{66a,66b} R. Stamen,^{59a} S. Stamm,¹⁹ E. Stanecka,⁸² R. W. Stanek,⁶
C. Stancu,^{72a} B. Stanislaus,¹³² M. M. Stanitzki,⁴⁴ B. Stapf,¹¹⁸ S. Stapnes,¹³¹ E. A. Starchenko,¹²¹ G. H. Stark,¹⁴³ J. Stark,⁵⁶
S. H. Stark,³⁹ P. Staroba,¹³⁸ P. Starovoitov,^{59a} S. Stärz,¹⁰¹ R. Staszewski,⁸² M. Stegler,⁴⁴ P. Steinberg,²⁹ B. Stelzer,¹⁴⁹
H. J. Stelzer,³⁵ O. Stelzer-Chilton,^{165a} H. Stenzel,⁵⁴ T. J. Stevenson,⁹⁰ G. A. Stewart,³⁵ M. C. Stockton,³⁵ G. Stoicea,^{27b}
P. Stolte,⁵¹ S. Stonjek,¹¹³ A. Straessner,⁴⁶ J. Strandberg,¹⁵¹ S. Strandberg,^{43a,43b} M. Strauss,¹²⁵ P. Strizenec,^{28b} R. Ströhmer,¹⁷⁴
D. M. Strom,¹²⁸ R. Stroynowski,⁴¹ A. Strubig,⁴⁸ S. A. Stucci,²⁹ B. Stugu,¹⁷ J. Stupak,¹²⁵ N. A. Styles,⁴⁴ D. Su,¹⁵⁰ J. Su,¹³⁶
S. Suchek,^{59a} Y. Sugaya,¹³⁰ M. Suk,¹³⁹ V. V. Sulin,¹⁰⁸ M. J. Sullivan,⁸⁸ D. M. S. Sultan,⁵² S. Sultansoy,^{4c} T. Sumida,⁸³
S. Sun,¹⁰³ X. Sun,³ K. Suruliz,¹⁵³ C. J. E. Suster,¹⁵⁴ M. R. Sutton,¹⁵³ S. Suzuki,⁷⁹ M. Svatos,¹³⁸ M. Swiatlowski,³⁶
S. P. Swift,² A. Sydorenko,⁹⁷ I. Sykora,^{28a} M. Sykora,¹⁴⁰ T. Sykora,¹⁴⁰ D. Ta,⁹⁷ K. Tackmann,^{44,t} J. Taenzer,¹⁵⁸ A. Taffard,¹⁶⁸
R. Tahirout,^{165a} E. Tahirovic,⁹⁰ N. Taiblum,¹⁵⁸ H. Takai,²⁹ R. Takashima,⁸⁴ E. H. Takasugi,¹¹³ K. Takeda,⁸⁰ T. Takeshita,¹⁴⁷
Y. Takubo,⁷⁹ M. Talby,⁹⁹ A. A. Talyshev,^{120b,120a} J. Tanaka,¹⁶⁰ M. Tanaka,¹⁶² R. Tanaka,¹²⁹ B. B. Tannenwald,¹²³
S. Tapia Araya,^{144b} S. Tapprogge,⁹⁷ A. Tarek Abouelfadl Mohamed,¹³³ S. Tarem,¹⁵⁷ G. Tarna,^{27b,q} G. F. Tartarelli,^{66a}
P. Tas,¹⁴⁰ M. Tasevsky,¹³⁸ T. Tashiro,⁸³ E. Tassi,^{40b,40a} A. Tavares Delgado,^{137a,137b} Y. Tayalati,^{34e} A. C. Taylor,¹¹⁶
A. J. Taylor,⁴⁸ G. N. Taylor,¹⁰² P. T. E. Taylor,¹⁰² W. Taylor,^{165b} A. S. Tee,⁸⁷ R. Teixeira De Lima,¹⁵⁰ P. Teixeira-Dias,⁹¹
H. Ten Kate,³⁵ J. J. Teoh,¹¹⁸ S. Terada,⁷⁹ K. Terashi,¹⁶⁰ J. Terron,⁹⁶ S. Terzo,¹⁴ M. Testa,⁴⁹ R. J. Teuscher,^{164,n} S. J. Thais,¹⁸⁰
T. Thevenaux-Pelzer,⁴⁴ F. Thiele,³⁹ D. W. Thomas,⁹¹ J. P. Thomas,²¹ A. S. Thompson,⁵⁵ P. D. Thompson,²¹
L. A. Thomsen,¹⁸⁰ E. Thomson,¹³⁴ Y. Tian,³⁸ R. E. Ticse Torres,⁵¹ V. O. Tikhomirov,^{108,uu} Yu. A. Tikhonov,^{120b,120a}
S. Timoshenko,¹¹⁰ P. Tipton,¹⁸⁰ S. Tisserant,⁹⁹ K. Todome,¹⁶² S. Todorova-Nova,⁵ S. Todt,⁴⁶ J. Tojo,⁸⁵ S. Tokár,^{28a}
K. Tokushuku,⁷⁹ E. Tolley,¹²³ K. G. Tomiwa,^{32c} M. Tomoto,¹¹⁵ L. Tompkins,^{150,gg} K. Toms,¹¹⁶ B. Tong,⁵⁷ P. Tornambe,⁵⁰
E. Torrence,¹²⁸ H. Torres,⁴⁶ E. Torró Pastor,¹⁴⁵ C. Tosciri,¹³² J. Toth,^{99,vv} F. Touchard,⁹⁹ D. R. Tovey,¹⁴⁶ C. J. Treado,¹²²

T. Trefzger,¹⁷⁴ F. Tresoldi,¹⁵³ A. Tricoli,²⁹ I. M. Trigger,^{165a} S. Trincas-Duvold,¹³³ W. Trischuk,¹⁶⁴ B. Trocme,⁵⁶
A. Trofymov,¹²⁹ C. Troncon,^{66a} M. Trovatelli,¹⁷³ F. Trovato,¹⁵³ L. Truong,^{32b} M. Trzebinski,⁸² A. Trzupek,⁸² F. Tsai,⁴⁴
J. C.-L. Tseng,¹³² P. V. Tsiarashka,^{105,ii} A. Tsirigotis,¹⁵⁹ N. Tsirintanis,⁹ V. Tsiskaridze,¹⁵² E. G. Tskhadadze,^{156a}
I. I. Tsukerman,¹⁰⁹ V. Tsulaia,¹⁸ S. Tsuno,⁷⁹ D. Tsybychev,^{152,163} Y. Tu,^{61b} A. Tudorache,^{27b} V. Tudorache,^{27b}
T. T. Tumbure,^{27a} A. N. Tuna,⁵⁷ S. Turchikhin,⁷⁷ D. Turgeman,¹⁷⁷ I. Turk Cakir,^{4b,ww} R. Turra,^{66a} P. M. Tuts,³⁸ S. Tzamarias,¹⁵⁹
E. Tzovara,⁹⁷ G. Uccchielli,⁴⁵ I. Ueda,⁷⁹ M. Ughetto,^{43a,43b} F. Ukegawa,¹⁶⁶ G. Unal,³⁵ A. Undrus,²⁹ G. Unel,¹⁶⁸
F. C. Ungaro,¹⁰² Y. Unno,⁷⁹ K. Uno,¹⁶⁰ J. Urban,^{28b} P. Urquijo,¹⁰² G. Usai,⁸ J. Usui,⁷⁹ L. Vacavant,⁹⁹ V. Vacek,¹³⁹
B. Vachon,¹⁰¹ K. O. H. Vadla,¹³¹ A. Vaidya,⁹² C. Valderanis,¹¹² E. Valdes Santurio,^{43a,43b} M. Valente,⁵² S. Valentinetti,^{23b,23a}
A. Valero,¹⁷¹ L. Valéry,⁴⁴ R. A. Vallance,²¹ A. Vallier,⁵ J. A. Valls Ferrer,¹⁷¹ T. R. Van Daalen,¹⁴ H. Van der Graaf,¹¹⁸
P. Van Gemmeren,⁶ I. Van Vulpen,¹¹⁸ M. Vanadia,^{71a,71b} W. Vandelli,³⁵ A. Vaniachine,¹⁶³ P. Vankov,¹¹⁸ R. Vari,^{70a}
E. W. Varnes,⁷ C. Varni,^{53b,53a} T. Varol,⁴¹ D. Varouchas,¹²⁹ K. E. Varvell,¹⁵⁴ G. A. Vasquez,^{144b} J. G. Vasquez,¹⁸⁰
F. Vazeille,³⁷ D. Vazquez Furelos,¹⁴ T. Vazquez Schroeder,³⁵ J. Veatch,⁵¹ V. Vecchio,^{72a,72b} L. M. Veloce,¹⁶⁴ F. Veloso,^{137a,137c}
S. Veneziano,^{70a} A. Ventura,^{65a,65b} N. Venturi,³⁵ V. Vercesi,^{68a} M. Verducci,^{72a,72b} C. M. Vergel Infante,⁷⁶ C. Vergis,²⁴
W. Verkerke,¹¹⁸ A. T. Vermeulen,¹¹⁸ J. C. Vermeulen,¹¹⁸ M. C. Vetterli,^{149,f} N. Viaux Maira,^{144b} M. Vicente Barreto Pinto,⁵²
I. Vichou,^{170,a} T. Vickey,¹⁴⁶ O. E. Vickey Boeriu,¹⁴⁶ G. H. A. Viehhauser,¹³² S. Viel,¹⁸ L. Vigani,¹³² M. Villa,^{23b,23a}
M. Villaplana Perez,^{66a,66b} E. Vilucchi,⁴⁹ M. G. Vincet,³³ V. B. Vinogradov,⁷⁷ A. Vishwakarma,⁴⁴ C. Vittori,^{23b,23a}
I. Vivarelli,¹⁵³ S. Vlachos,¹⁰ M. Vogel,¹⁷⁹ P. Vokac,¹³⁹ G. Volpi,¹⁴ S. E. von Buddenbrock,^{32c} E. Von Toerne,²⁴ V. Vorobel,¹⁴⁰
K. Vorobev,¹¹⁰ M. Vos,¹⁷¹ J. H. Vossebeld,⁸⁸ N. Vranjes,¹⁶ M. Vranjes Milosavljevic,¹⁶ V. Vrbica,¹³⁹ M. Vreeswijk,¹¹⁸
T. Šfiligoj,⁸⁹ R. Vuillermet,³⁵ I. Vukotic,³⁶ T. Ženiš,^{28a} L. Živković,¹⁶ P. Wagner,²⁴ W. Wagner,¹⁷⁹ J. Wagner-Kuhr,¹¹²
H. Wahlberg,⁸⁶ S. Wahrmond,⁴⁶ K. Wakamiya,⁸⁰ V. M. Walbrecht,¹¹³ J. Walder,⁸⁷ R. Walker,¹¹² S. D. Walker,⁹¹
W. Walkowiak,¹⁴⁸ V. Wallangen,^{43a,43b} A. M. Wang,⁵⁷ C. Wang,^{58b} F. Wang,¹⁷⁸ H. Wang,¹⁸ H. Wang,³ J. Wang,¹⁵⁴
J. Wang,^{59b} P. Wang,⁴¹ Q. Wang,¹²⁵ R.-J. Wang,¹³³ R. Wang,^{58a} R. Wang,⁶ S. M. Wang,¹⁵⁵ W. T. Wang,^{58a} W. Wang,^{15c,xx}
W. X. Wang,^{58a,xx} Y. Wang,^{58a,kk} Z. Wang,^{58c} C. Wanotayaroj,⁴⁴ A. Warburton,¹⁰¹ C. P. Ward,³¹ D. R. Wardrope,⁹²
A. Washbrook,⁴⁸ P. M. Watkins,²¹ A. T. Watson,²¹ M. F. Watson,²¹ G. Watts,¹⁴⁵ S. Watts,⁹⁸ B. M. Waugh,⁹² A. F. Webb,¹¹
S. Webb,⁹⁷ C. Weber,¹⁸⁰ M. S. Weber,²⁰ S. A. Weber,³³ S. M. Weber,^{59a} A. R. Weidberg,¹³² J. Weingarten,⁴⁵ M. Weirich,⁹⁷
C. Weiser,⁵⁰ P. S. Wells,³⁵ T. Wenaus,²⁹ T. Wengler,³⁵ S. Wenig,³⁵ N. Wermes,²⁴ M. D. Werner,⁷⁶ P. Werner,³⁵ M. Wessels,^{59a}
T. D. Weston,²⁰ K. Whalen,¹²⁸ N. L. Whallon,¹⁴⁵ A. M. Wharton,⁸⁷ A. S. White,¹⁰³ A. White,⁸ M. J. White,¹ R. White,^{144b}
D. Whiteson,¹⁶⁸ B. W. Whitmore,⁸⁷ F. J. Wickens,¹⁴¹ W. Wiedenmann,¹⁷⁸ M. Wielers,¹⁴¹ C. Wigglesworth,³⁹
L. A. M. Wiik-Fuchs,⁵⁰ F. Wilk,⁹⁸ H. G. Wilkens,³⁵ L. J. Wilkins,⁹¹ H. H. Williams,¹³⁴ S. Williams,³¹ C. Willis,¹⁰⁴
S. Willocq,¹⁰⁰ J. A. Wilson,²¹ I. Wingerter-Seez,⁵ E. Winkels,¹⁵³ F. Winklmeier,¹²⁸ O. J. Winston,¹⁵³ B. T. Winter,⁵⁰
M. Wittgen,¹⁵⁰ M. Wobisch,⁹³ A. Wolf,⁹⁷ T. M. H. Wolf,¹¹⁸ R. Wolff,⁹⁹ J. Wollrath,⁵⁰ M. W. Wolter,⁸² H. Wolters,^{137a,137c}
V. W. S. Wong,¹⁷² N. L. Woods,¹⁴³ S. D. Worm,²¹ B. K. Wosiek,⁸² K. W. Woźniak,⁸² K. Wraight,⁵⁵ M. Wu,³⁶ S. L. Wu,¹⁷⁸
X. Wu,⁵² Y. Wu,^{58a} T. R. Wyatt,⁹⁸ B. M. Wynne,⁴⁸ S. Xella,³⁹ Z. Xi,¹⁰³ L. Xia,¹⁷⁵ D. Xu,^{15a} H. Xu,^{58a,q} L. Xu,²⁹ T. Xu,¹⁴²
W. Xu,¹⁰³ Z. Xu,¹⁵⁰ B. Yabsley,¹⁵⁴ S. Yacoub,^{32a} K. Yajima,¹³⁰ D. P. Yallup,⁹² D. Yamaguchi,¹⁶² Y. Yamaguchi,¹⁶²
A. Yamamoto,⁷⁹ T. Yamanaka,¹⁶⁰ F. Yamane,⁸⁰ M. Yamatani,¹⁶⁰ T. Yamazaki,¹⁶⁰ Y. Yamazaki,⁸⁰ Z. Yan,²⁵ H. J. Yang,^{58c,58d}
H. T. Yang,¹⁸ S. Yang,⁷⁵ Y. Yang,¹⁶⁰ Z. Yang,¹⁷ W.-M. Yao,¹⁸ Y. C. Yap,⁴⁴ Y. Yasu,⁷⁹ E. Yatsenko,^{58c,58d} J. Ye,⁴¹ S. Ye,²⁹
I. Yeletsikh,⁷⁷ E. Yigitbasi,²⁵ E. Yildirim,⁹⁷ K. Yorita,¹⁷⁶ K. Yoshihara,¹³⁴ C. J. S. Young,³⁵ C. Young,¹⁵⁰ J. Yu,⁸ J. Yu,⁷⁶
X. Yue,^{59a} S. P. Yuen,²⁴ B. Zabinski,⁸² G. Zacharis,¹⁰ E. Zaffaroni,⁵² R. Zaidan,¹⁴ A. M. Zaitsev,^{121,oo} T. Zakareishvili,^{156b}
N. Zakharchuk,³³ S. Zambito,⁵⁷ D. Zanzi,³⁵ D. R. Zaripovas,⁵⁵ S. V. ZeiBner,⁴⁵ C. Zeitnitz,¹⁷⁹ G. Zemaityte,¹³² J. C. Zeng,¹⁷⁰
Q. Zeng,¹⁵⁰ O. Zenin,¹²¹ D. Zerwas,¹²⁹ M. Zgubič,¹³² D. F. Zhang,^{58b} D. Zhang,¹⁰³ F. Zhang,¹⁷⁸ G. Zhang,^{58a} G. Zhang,^{15b}
H. Zhang,^{15c} J. Zhang,⁶ L. Zhang,^{15c} L. Zhang,^{58a} M. Zhang,¹⁷⁰ P. Zhang,^{15c} R. Zhang,^{58a} R. Zhang,²⁴ X. Zhang,^{58b}
Y. Zhang,^{15d} Z. Zhang,¹²⁹ P. Zhao,⁴⁷ Y. Zhao,^{58b,129,aa} Z. Zhao,^{58a} A. Zhemchugov,⁷⁷ Z. Zheng,¹⁰³ D. Zhong,¹⁷⁰ B. Zhou,¹⁰³
C. Zhou,¹⁷⁸ M. S. Zhou,^{15d} M. Zhou,¹⁵² N. Zhou,^{58c} Y. Zhou,⁷ C. G. Zhu,^{58b} H. L. Zhu,^{58a} H. Zhu,^{15a} J. Zhu,¹⁰³ Y. Zhu,^{58a}
X. Zhuang,^{15a} K. Zhukov,¹⁰⁸ V. Zhulanov,^{120b,120a} A. Zibell,¹⁷⁴ D. Zieminska,⁶³ N. I. Zimine,⁷⁷ S. Zimmermann,⁵⁰
Z. Zinonos,¹¹³ M. Ziolkowski,¹⁴⁸ G. Zobernig,¹⁷⁸ A. Zoccoli,^{23b,23a} K. Zoch,⁵¹ T. G. Zorbas,¹⁴⁶ R. Zou,³⁶
M. Zur Nedden,¹⁹ and L. Zwalinski³⁵

(ATLAS Collaboration)

- ¹*Department of Physics, University of Adelaide, Adelaide, Australia*
- ²*Physics Department, SUNY Albany, Albany, New York, USA*
- ³*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
- ^{4a}*Department of Physics, Ankara University, Ankara, Turkey*
- ^{4b}*Istanbul Aydin University, Istanbul, Turkey*
- ^{4c}*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
- ⁵*LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France*
- ⁶*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*
- ⁷*Department of Physics, University of Arizona, Tucson, Arizona, USA*
- ⁸*Department of Physics, University of Texas at Arlington, Arlington, Texas, USA*
- ⁹*Physics Department, National and Kapodistrian University of Athens, Athens, Greece*
- ¹⁰*Physics Department, National Technical University of Athens, Zografou, Greece*
- ¹¹*Department of Physics, University of Texas at Austin, Austin, Texas, USA*
- ^{12a}*Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*
- ^{12b}*Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*
- ^{12c}*Department of Physics, Bogazici University, Istanbul, Turkey*
- ^{12d}*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
- ¹³*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
- ¹⁴*Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain*
- ^{15a}*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
- ^{15b}*Physics Department, Tsinghua University, Beijing, China*
- ^{15c}*Department of Physics, Nanjing University, Nanjing, China*
- ^{15d}*University of Chinese Academy of Science (UCAS), Beijing, China*
- ¹⁶*Institute of Physics, University of Belgrade, Belgrade, Serbia*
- ¹⁷*Department for Physics and Technology, University of Bergen, Bergen, Norway*
- ¹⁸*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA*
- ¹⁹*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
- ²⁰*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
- ²¹*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
- ²²*Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia*
- ^{23a}*Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy*
- ^{23b}*INFN Sezione di Bologna, Bologna, Italy*
- ²⁴*Physikalisches Institut, Universität Bonn, Bonn, Germany*
- ²⁵*Department of Physics, Boston University, Boston, Massachusetts, USA*
- ²⁶*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
- ^{27a}*Transilvania University of Brasov, Brasov, Romania*
- ^{27b}*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
- ^{27c}*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
- ^{27d}*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania*
- ^{27e}*University Politehnica Bucharest, Bucharest, Romania*
- ^{27f}*West University in Timisoara, Timisoara, Romania*
- ^{28a}*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
- ^{28b}*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- ²⁹*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
- ³⁰*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
- ³¹*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ^{32a}*Department of Physics, University of Cape Town, Cape Town, South Africa*
- ^{32b}*Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa*
- ^{32c}*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- ³³*Department of Physics, Carleton University, Ottawa, Ontario, Canada*
- ^{34a}*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco*
- ^{34b}*Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN), Rabat, Morocco*
- ^{34c}*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*

- ^{34d}*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
^{34e}*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
³⁵*CERN, Geneva, Switzerland*
³⁶*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
³⁷*LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
³⁸*Nevis Laboratory, Columbia University, Irvington, New York, USA*
³⁹*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
^{40a}*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
^{40b}*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
⁴¹*Physics Department, Southern Methodist University, Dallas, Texas, USA*
⁴²*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
^{43a}*Department of Physics, Stockholm University, Sweden*
^{43b}*Oskar Klein Centre, Stockholm, Sweden*
⁴⁴*Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
⁴⁵*Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
⁴⁶*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
⁴⁷*Department of Physics, Duke University, Durham, North Carolina, USA*
⁴⁸*SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
⁴⁹*INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
⁵⁰*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
⁵¹*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
⁵²*Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
^{53a}*Dipartimento di Fisica, Università di Genova, Genova, Italy*
^{53b}*INFN Sezione di Genova, Genova, Italy*
⁵⁴*II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
⁵⁵*SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
⁵⁶*LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
⁵⁷*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
^{58a}*Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China*
^{58b}*Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China*
^{58c}*School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai, China*
^{58d}*Tsung-Dao Lee Institute, Shanghai, China*
^{59a}*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
^{59b}*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
⁶⁰*Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
^{61a}*Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China*
^{61b}*Department of Physics, University of Hong Kong, Hong Kong, China*
^{61c}*Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
⁶²*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
⁶³*Department of Physics, Indiana University, Bloomington, Indiana, USA*
^{64a}*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
^{64b}*ICTP, Trieste, Italy*
^{64c}*Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
^{65a}*INFN Sezione di Lecce, Lecce, Italy*
^{65b}*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
^{66a}*INFN Sezione di Milano, Milano, Italy*
^{66b}*Dipartimento di Fisica, Università di Milano, Milano, Italy*
^{67a}*INFN Sezione di Napoli, Napoli, Italy*
^{67b}*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
^{68a}*INFN Sezione di Pavia, Pavia, Italy*
^{68b}*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
^{69a}*INFN Sezione di Pisa, Pisa, Italy*
^{69b}*Dipartimento di Fisica E.Fermi, Università di Pisa, Pisa, Italy*
^{70a}*INFN Sezione di Roma, Roma, Italy*
^{70b}*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
^{71a}*INFN Sezione di Roma Tor Vergata, Roma, Italy*

- ^{71b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
^{72a}*INFN Sezione di Roma Tre, Roma, Italy*
^{72b}*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
^{73a}*INFN-TIFPA, Trento, Italy*
^{73b}*Università degli Studi di Trento, Trento, Italy*
⁷⁴*Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
⁷⁵*University of Iowa, Iowa City, Iowa, USA*
⁷⁶*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
⁷⁷*Joint Institute for Nuclear Research, Dubna, Russia*
^{78a}*Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil*
^{78b}*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
^{78c}*Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil*
^{78d}*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
⁷⁹*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
⁸⁰*Graduate School of Science, Kobe University, Kobe, Japan*
^{81a}*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
^{81b}*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
⁸²*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
⁸³*Faculty of Science, Kyoto University, Kyoto, Japan*
⁸⁴*Kyoto University of Education, Kyoto, Japan*
⁸⁵*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
⁸⁶*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
⁸⁷*Physics Department, Lancaster University, Lancaster, United Kingdom*
⁸⁸*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
⁸⁹*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
⁹⁰*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
⁹¹*Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
⁹²*Department of Physics and Astronomy, University College London, London, United Kingdom*
⁹³*Louisiana Tech University, Ruston, Louisiana, USA*
⁹⁴*Fysiska institutionen, Lunds universitet, Lund, Sweden*
⁹⁵*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*
⁹⁶*Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
⁹⁷*Institut für Physik, Universität Mainz, Mainz, Germany*
⁹⁸*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
⁹⁹*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
¹⁰⁰*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
¹⁰¹*Department of Physics, McGill University, Montreal, Québec, Canada*
¹⁰²*School of Physics, University of Melbourne, Victoria, Australia*
¹⁰³*Department of Physics, University of Michigan, Ann Arbor, Michigan, USA*
¹⁰⁴*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
¹⁰⁵*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
¹⁰⁶*Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus*
¹⁰⁷*Group of Particle Physics, University of Montreal, Montreal, Québec, Canada*
¹⁰⁸*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
¹⁰⁹*Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
¹¹⁰*National Research Nuclear University MEPhI, Moscow, Russia*
¹¹¹*D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
¹¹²*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
¹¹³*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
¹¹⁴*Nagasaki Institute of Applied Science, Nagasaki, Japan*
¹¹⁵*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
¹¹⁶*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*

- ¹¹⁷*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
- ¹¹⁸*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- ¹¹⁹*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
- ^{120a}*Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia*
- ^{120b}*Novosibirsk State University Novosibirsk, Russia*
- ¹²¹*Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia*
- ¹²²*Department of Physics, New York University, New York, New York, USA*
- ¹²³*The Ohio State University, Columbus, Ohio, USA*
- ¹²⁴*Faculty of Science, Okayama University, Okayama, Japan*
- ¹²⁵*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
- ¹²⁶*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
- ¹²⁷*Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic*
- ¹²⁸*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
- ¹²⁹*LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
- ¹³⁰*Graduate School of Science, Osaka University, Osaka, Japan*
- ¹³¹*Department of Physics, University of Oslo, Oslo, Norway*
- ¹³²*Department of Physics, Oxford University, Oxford, United Kingdom*
- ¹³³*LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*
- ¹³⁴*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
- ¹³⁵*Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia*
- ¹³⁶*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
- ^{137a}*Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal*
- ^{137b}*Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
- ^{137c}*Departamento de Física, Universidade de Coimbra, Coimbra, Portugal*
- ^{137d}*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
- ^{137e}*Departamento de Física, Universidade do Minho, Braga, Portugal*
- ^{137f}*Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain*
- ^{137g}*Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal*
- ¹³⁸*Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
- ¹³⁹*Czech Technical University in Prague, Prague, Czech Republic*
- ¹⁴⁰*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
- ¹⁴¹*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹⁴²*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- ¹⁴³*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
- ^{144a}*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
- ^{144b}*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
- ¹⁴⁵*Department of Physics, University of Washington, Seattle, Washington, USA*
- ¹⁴⁶*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- ¹⁴⁷*Department of Physics, Shinshu University, Nagano, Japan*
- ¹⁴⁸*Department Physik, Universität Siegen, Siegen, Germany*
- ¹⁴⁹*Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada*
- ¹⁵⁰*SLAC National Accelerator Laboratory, Stanford, California, USA*
- ¹⁵¹*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
- ¹⁵²*Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA*
- ¹⁵³*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
- ¹⁵⁴*School of Physics, University of Sydney, Sydney, Australia*
- ¹⁵⁵*Institute of Physics, Academia Sinica, Taipei, Taiwan*
- ^{156a}*E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi, Georgia*
- ^{156b}*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
- ¹⁵⁷*Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
- ¹⁵⁸*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
- ¹⁵⁹*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
- ¹⁶⁰*International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
- ¹⁶¹*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*

- ¹⁶²*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
¹⁶³*Tomsk State University, Tomsk, Russia*
¹⁶⁴*Department of Physics, University of Toronto, Toronto, Ontario, Canada*
^{165a}*TRIUMF, Vancouver, British Columbia, Canada*
^{165b}*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
¹⁶⁶*Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
¹⁶⁷*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
¹⁶⁸*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
¹⁶⁹*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
¹⁷⁰*Department of Physics, University of Illinois, Urbana, Illinois, USA*
¹⁷¹*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*
¹⁷²*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
¹⁷³*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*
¹⁷⁴*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
¹⁷⁵*Department of Physics, University of Warwick, Coventry, United Kingdom*
¹⁷⁶*Waseda University, Tokyo, Japan*
¹⁷⁷*Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel*
¹⁷⁸*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
¹⁷⁹*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
¹⁸⁰*Department of Physics, Yale University, New Haven, Connecticut, USA*
¹⁸¹*Yerevan Physics Institute, Yerevan, Armenia*

^aDeceased.

^bAlso at Department of Physics, King's College London, London, United Kingdom.

^cAlso at Istanbul University, Dept. of Physics, Istanbul, Turkey.

^dAlso at Instituto de Física Teórica de la Universidad Autónoma de Madrid, Spain.

^eAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

^fAlso at TRIUMF, Vancouver, British Columbia, Canada.

^gAlso at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.

^hAlso at Department of Physics, University of Fribourg, Fribourg, Switzerland.

ⁱAlso at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

^jAlso at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

^kAlso at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

^lAlso at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.

^mAlso at Università di Napoli Parthenope, Napoli, Italy.

ⁿAlso at Institute of Particle Physics (IPP), Canada.

^oAlso at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany.

^pAlso at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

^qAlso at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.

^rAlso at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

^sAlso at Borough of Manhattan Community College, City University of New York, New York, USA.

^tAlso at Department of Physics, California State University, Fresno, California, USA.

^uAlso at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

^vAlso at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

^wAlso at Louisiana Tech University, Ruston, Louisiana, USA.

^xAlso at California State University, East Bay, California, USA.

^yAlso at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

^zAlso at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.

^{aa}Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.

^{bb}Also at Graduate School of Science, Osaka University, Osaka, Japan.

^{cc}Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.

^{dd}Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

^{ee}Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

^{ff}Also at CERN, Geneva, Switzerland.

^{gg}Also at Department of Physics, Stanford University, Stanford, California, USA.

^{hh}Also at Manhattan College, New York, New York, USA.

ⁱⁱAlso at Joint Institute for Nuclear Research, Dubna, Russia.

- ^{jj}Also at Hellenic Open University, Patras, Greece.
- ^{kk}Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France.
- ^{ll}Also at The City College of New York, New York, New York, USA.
- ^{mm}Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain.
- ⁿⁿAlso at Department of Physics, California State University, Sacramento, California, USA.
- ^{oo}Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- ^{pp}Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
- ^{qq}Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
- ^{rr}Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
- ^{ss}Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.
- ^{tt}Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
- ^{uu}Also at National Research Nuclear University MEPhI, Moscow, Russia.
- ^{vv}Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- ^{ww}Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
- ^{xx}Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.